# BOND BEHAVIOUR OF SEVEN-WIRE STRANDS UNDER PULSATING LOADS

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY



By

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AUGUST, 1981

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CERTIFICATE

This is to cerify that the work towards this thesis entitled " BOND BEHAVIOUR OF SEVEN-WIRE STRANDS UNDER PULSATING LOADS" by Satish Kumar Raina has been carried out under my supervision and the thesis has not been submitted elsewhere for a degree.

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August, 1981

## ACKNOWLDGEMENT

I take this opportunity to thank

- Prof. P. Dayaratnam for his invaluable and constant encouragement.

- and those who have rendered help at all stages of the work.

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## ABSTRACT

Pretensioning system of prestressed concrete is commonly used in the precast prestress concrete industry. A dominating trend has developed in the recent years towards the use of prestressing strands.

Generally, concrete is prestressed by using a number of strands or wires. The bond between the strand or wire and concrete is likely to vary depending on the method of construction and the size and number of strands. In the present investigation, a study has been carried out under pulsating loads for strands which have developed a partial bond. The study has been done on a seven-wire strand of 6.35 mm diameter.

Pull-out tests were carried out to study the bond strength of the strand under tension with variable embedment lengths. For this, three sets of specimens with different embedment lengths, were tested.

For studying the bond behaviour under puslating loads, tests on hinged beams were performed. Three sets of beams were tested under static and pulsating loads. One of the sets was provided with a secondary anchorage device. This device consisted of a washer and a nut welded to the free end of the strand.

The secondary anchorage system improved the bond-cum-anchorage behaviour of the strand under pulsating loads and could be used to minimize further deterioration of load carrying capacity of such a beam.

# CHAPTER - I

## GENERAL INTRODUCTION AND PROBLEM STATEMENT

### 1.1: INTRODUCTION:

Multi-wire high tensile steel strands are being used in prestressed concrete for various purposes. Strands consisting of two, three and seven-wire are being utilised in the construction of pretensioned prestressed concrete beams, electric poles, railway sleepers etc.

Some of the advantages of strands as compared to plain high tensile steel wires are as follows:

(1) In case of strand, HTS wires are stranded together to form a strand. The helical wave formation thus obtained on the surface of the strand results in higher bond between concrete and the strand as compared to plain HTS wire of equal diameter. Thus the former reduces the bond length.

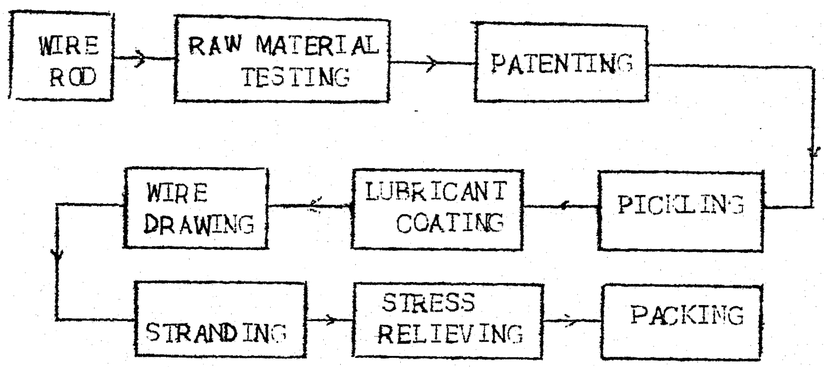
(2) The number of wires to be handled to give the same prestressing force is less, thus giving some economy while prestressing.

(3) The ultimate strength of strands would be more as compared to plain HTS wire of same diameter as the former consist of a number of smaller diameter HTS wires. The strength of small wires drawn from the same material is higher than the larger diameter wires.

## 1.2: PROPERTIES OF 6.35 mm (1/4 inch) SEVEN-WIRE STRAND:

### 1.2.1: MANUFACTURE:

High tensile rod is the raw material for the manufacture of HTS wire and strands. The HTS wires are cold drawn from the rod and smaller diameter wires of very high tensile strength are used for making strands. The manufacturing process of strands involves following steps:




### 1.2.2: CHEMICAL COMPOSITION AND SPECIFICATIONS:

The approximate chemical composition of high tensile steel wires, of which the strands are made, are (1)

Carbon - 0.60 to 0.90%    Manganese - 0.50 to 0.90%

Silicon - 0.10 to 0.35%    Sulphur - 0.05% maximum,

Phosphorus - 0.057% maximum.

The specification of seven-wire strand as per ASTM 416 - 74 (2), is given in Table - 1.1.

TABLE 1.1: SPECIFICATION OF SEVEN-WIRE 6.35 mm dia.STRAND

<table>
<tr><td rowspan="7">Standard ASTM/4 416-74 Grade – 250</td><td colspan="2">Nominal diameter</td><td colspan="2">Nominal area of strand</td><td colspan="2">Breaking Strength</td><td colspan="2">Pitch (∅ is dia. of strand)</td></tr>
<tr><td>Inch.</td><td>mm</td><td>mm²</td><td>inch²</td><td>lbs</td><td>kN</td><td colspan="2"></td></tr>
<tr><td>1/4</td><td>6.35</td><td>23.22</td><td>0.036</td><td>9000</td><td>40.32</td><td colspan="2">12∅ – 16∅</td></tr>
<tr><td colspan="2">Minimum load at 1% extension</td><td colspan="3">Minimum % elongation in 24 inch(30[illegible].8mm)</td><td colspan="3">Difference between Centre wire and outer wire</td></tr>
<tr><td>lbs</td><td>kN</td><td colspan="3"></td><td>inch</td><td colspan="2">mm</td></tr>
<tr><td>7650</td><td>34.70</td><td colspan="3">3.5</td><td>0.001</td><td colspan="2">0.025</td></tr>
</table>

## 1.3: LIVE LOADS:

The self weight of the structure and any other load which is fixed in position and magnitude is known as dead load. Any load whose application and release occurs from time to time is the live load. Since live load is a time dependent phenomenon and random in nature, the exact probability of occurance and mangitude can not be predicted. Live load can be applied in a repeated cyclic manner causing elastic and plastic strains of alternate sense or of same sense.

## 1.4 OVER LOAD CONDITIONS:

Live loads acting on the structure are usually considered as deterministic in design, though the actual occurence and magnitude of such loads are not exactly known to the designer.

Wind velocity reaches different peak values in different time intervals. Since velocity of wind is proportional to the forces exerted by wind on a structure, higher velocity would mean higher load compared to the expected maximum load and these higher loads can be termed as overloads. Similar loads may be introduced due to earthquakes.

A structure is thus said to be overloaded when the stress level at any point of the structure increases beyond the normal permissible stress level due to loads other than the normal working loads.

To design a structure to an exact load pattern is not possible in a deterministic design. Hence, a proper idealisation and a selection of design load has to be done. A typical load characteristic curve is shown in Fig.1.1.

A particular load frequency may be idealized either by static criteria or by energy criteria. An approximate typical idealized load frequency is shown in Fig.1.2. It is clear from the figure that different peak loads occur in different time intervals during the lifespan of a structure. From the study of the frequency of different peak loads which are likely to occur during this lifespan of the structure, normal load is to be selected such that it will neither fail in its lifespan due to these unexpected overloads nor be overdesigned. For example,

referring to Fig. 1.2, if level 'A' is taken as the normal design load, then the structure will be called over designed because the occurence of such load may be one in a million. In that case, the structure is very much understressed almost throughout its lifespan. When load 'C' is chosen as the normal design load, the structure may suffer from serious damage or may collapse when the peak load level 'A' acts on the structure during its lifespan. Hence a design load 'B' may be selected such that it will be able to withstand the heavy stresses caused by the load level 'A' in its life period and at the same time will not be overdesigned. The load corresponding to load level 'A' may be termed as overload. Since the permissible stresses are not exceeded in case of load level 'B', it is selected as the design load. Thus a normal design load is that load at which full stresses are permitted in the working stress, or full load factors are applied in the ultimate load design.

## 1.5 : CONCEPT OF BOND ACTION IN PRESTRESSED CONCRETE :

### 1.5.1 : Nature of Bond :

Bond in pretensioned concrete beams is of two types viz. transfer bond and flexural bond. Transfer bond utilizes a part of the available tensile strength of the steel to establish compression in the concrete. Flexural bond results from the action of external loads on beams. After cracking, the increase in steel stress above effective prestress develops flexural bond stress between the steel and the concrete.

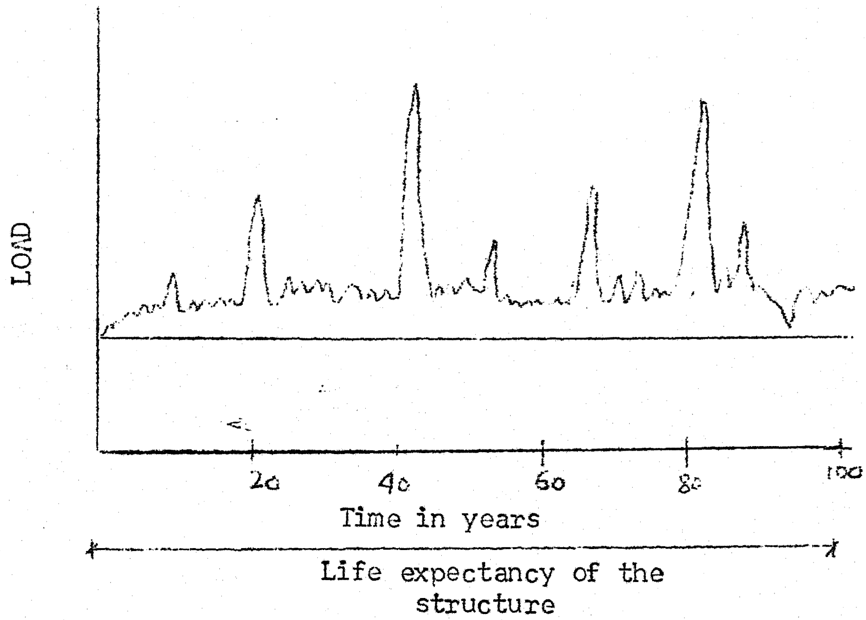



Fig. 1.1. Typical Load Characteristics

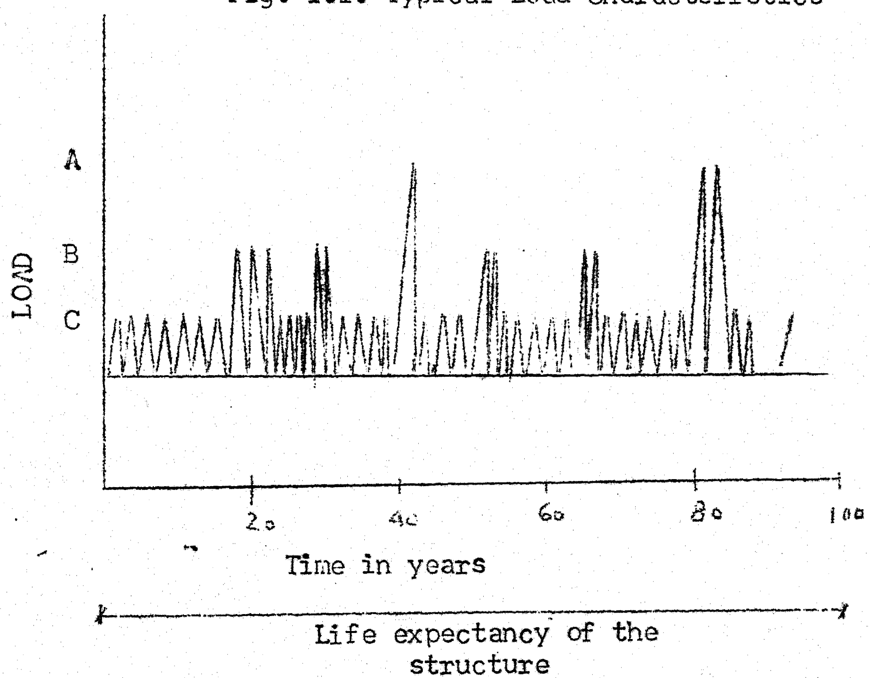



Fig. 1.2 Idealised Load Characteristics

The sum of the lengths required for transfer bond and flexural bond is called the development length or total bond length.

1.5.2: Transfer Bond:

Transfer bond exists near the free ends of the wires after the load in the tensioned strand has been transfered to the concrete member. The length over which this transfer of prestress is made is termed as transfer bond length and depends chiefly on amount of prestress, surface condition of the strand, the strength of concrete and the method of steel stress release. The factors contributing to bond performance are adhesion, friction and mechanical resistance between concrete and steel. In the transfer zone, reduction in the tensile strain of the steel does not equal the compressive strain in the concrete at the same point. There is a relative movement of steel and concrete and accordingly adhesion cannot contribute to prestress transfer. Friction is considered to be the principal agent causing stress transfer from pretensioning steel to concrete. As the tension in the strand is realeased, the strand diameter tends to increase, thus producing high radial pressure against the concrete, which in turn produces high frictional resistance in the transfer zone. Mechanical resistance probably contributes little to prestress transfer in the case of individual smooth wires, but it may be a factor of some significance in the case of a strand.

1.5.3: FLEXURE BOND:

According to Hanson and Kaar(3), flexural bond of significant magnitude exists only after the concrete beam has been loaded till cracking. When the concrete cracks, the bond stress in the immediate vicinity of the cracks rises to some limiting stress, slip occurs over a small portion of the strand length adjacent to the cracks, and the bond stress near the cracks is reduced to a low value. With continued increase in load, the high bond stress progresses as a wave from the original cracks toward the beam ends. The bond stress remaining behind the wave is always lower than the maximum value at the peak of the bond stress wave. If the peak of the high bond stress reaches the prestress transfer zone, the increase in steel stress resulting from the bond slip decreases the strand diameter, reduces the frictional bond resistance, and precipitates general bond slip. Following loss of frictional resistance, mechanical resistance is the only factor which can contribute to bond between concrete and steel. If the beam is prestressed with a clean smooth wire, this resistance will be small and the beam will quickly collapse after general slip has occured. If the beam is prestressed with a strand, the helical shape of the individual wires will provide sufficient mechanical resistance and the beam can support additional bond even after slip of strand at the beam ends.

## 1.6 : LITERATURE REVIEW:

The effectivenss of pre-tensioned prestressed concrete depends on the bond between the steel and concrete. This was a matter of concern from the begining and in the first large scale production of pretensioned prestressed concrete members in 1939.

The generally accepted view on this matter during the forties was that only wires up to 3mm. diameter could be anchored by bond. However, extensive development length tests of pretensioned prestressed concrete railroad ties at during the same period demonstrated that adequate anchorage could be obtained by bond even for 5 mm. diameter wires. It is, of course, economically advantageous to use as large a size of individual tensioned element as possible.

A great step forward in this direction was the introduction of the use of seven-wire strand in place of smooth wires. The idea was first experimented with, by B.J. Baskin (4), for bond, with success. Thus progressively larger sizes of seven-wire strands were used.

Since the bond study by Hoyer in 1939, many investigators (3,5,6,7,8,9) worked on the interaction between high tensile steel and concrete. Their work involved some of the factors, given below, on which the development length depends.

a) Type of steel, e.g., wire, strand.

b) Steel size (dia.)

c) Level of stress in steel.

d) Surface condition of steel - clean, oiled, rusted.

e) Concrete strength

f) Type of loading, e.g., static, repeated, impact.

g) Type of release, e.g., gradual, sudden.

h) Confining reinforcement around steel, e.g., helix or stirrups.

i) Time - dependent effect.

j) Consolidation and consistency of concrete around steel.

k) Amount of concrete coverage around steel.

Investigations by Janney (5,6) and by Hanson & Kaar (3) describe, in detail, two aspects of bond between prestressing steel and concrete. The prestressing force is transferred to the concrete by anchorage of steel over a certain distance from the ends of a member. The mechanism which provides this anchorage is known as transfer bond, and is primarily due to friction combined with the Poissons' effect, or lateral swelling of steel in the transfer zone. Flexural bond is a means by which the increased steel stress due to applied load is achieved. While the nature and distribution of these mechanisms are not clearly understood, the stresses due to flexural bond requirements, were found by Janney to progress in a wave towards the end of a prestressed member. When short span members are subjected to overloads; the flexural bond stress wave may invade the transfer region, precipitating loss of tendon anchorage at the ends of the member. This phenomenon, termed as "general bond failure" by earlier investigators, does not necessarily result in collapse of the member,

although it is apparent that its ability to stand additional load is questionable.

In the past, work has been done to study the behaviour of prestressed concrete beams under pulsating loads. This was to see the behaviour of the beam with respect to ultimate capacity, cumulative deflection and crack propagation. Not much work has been done to see the effect of pulsating loads on the bond behaviour of strands exclusively.

## 1.7 SCOPE OF INVESTIGATION AND PROBLEM STATEMENT:

There are two ways of inducing a prestressing force to a member. They are

(1) Post-tensioning (2) Pretensioning.

In case of post tensioning, concrete is cast while there is no stress in the tendon while keeping it free from bond with concrete. When the concrete has hardened, the tendons are stretched by hydraulic or mechanical jacks bearing against the concrete. The tendon force is transfered to the member through necessary anchorage wedges or similar blocks at the end of the member.

Pre-tensioning is obtained by stressing the tendons in position, to a predetermined amount and placing the concrete in

position while maintaining the stress in the tendons through an external force system. As the concrete hardens, the tensioned tendons are bonded; when the tendons are released from the external jacks, they will try to regain their original length. The concrete, as a result, is stressed. Thus the bond developed between steel and concrete transfers the prestressing force to the concrete. The mechanism of bond transfer is explained in Section 1.5.

In practice, in pretensioning systems, a number of tendons are required for transfering the prestressing force. These tendons are tensioned through hydraulic jacks and the strain is maintained during curing. When concrete has attained its transfer strength, the tendons are cut so as to transfer the prestressing force to the concrete. As soon as the tendons are cut, the tendons try to pull in. After a small amount of pull-in, it stabilizes and the load in the tensioned tendon is imparted to the concrete. In practice, it is quite possible that few tendons may have pulled in more as compared with the other tendons, thus depicting only partial bond between steel and concrete for these tendons. This may be because of poor compaction or formation of a void around the tendon. Such a tendon will not share the same load as compared to other tendons and may fail prematurely in bond under repeated loads.

The present study is thus aimed at the behaviour of such tendons under pulsating loads. Further, a study is also made to

strengthen the bond character by a mechanism consisting of secondary anchorage. For the present investigation, seven-wire strand of 6.35mm. dia. are used, the specifications of which are given in Table 1.1.

The work involves in subjecting the strand, embedded in concrete with different bond lengths, to repeated loads with the help of a hinged beam mechanism. Since the investigation is aimed at studying the bond behaviour of a single strand under repeated loads, it is necessary to design an arrangement which would transmit the repeated loads to the strand, without disturbing the bond length by formation of cracks and also to be safe in crushing, shear etc. For this an ideal solution is a hinged beam mechanism which serves the above purpose. The design of the hingedbeam is given in Appendix A. The secondary anchorage arrangement used to improve the bond performance, consisted of a washer and a nut welded to two free ends of the strands.

In general, structures are subjected to dead loads, superimposed loads, live loads and occasional peak loads. Dead loads are more or less permanent loads while live loads are repetitive in nature. In a laboratory the repetitive loads can be simulated by applying variable pulsating load at certain frequency with the help of a pulsator. Thus, we have two load bonds viz. upper bond and lower bond. The selection of the bonds is given in section (3.6.2).

For a real life structure it is said that it would be subjected to a maximum of one million cycles in its lifespan. Moreover, the real life structures are subjected to a comparatively low frequency. The experiment had to be conducted at such a frequency so as to minimize the time required.

The present investigation, to study the bond behaviour of strands, is, hence, formulated as follows.

(A) PULL OUT TEST:

Determination of average bond strength of 6.35 mm (1/4 inch) strand from pull out test, the only variable being the bond length.

(B) HINGED BEAM TEST WITH AND WITHOUT SECONDARY ANCHORAGE:

(i) Behaviour of beams, for ultimate strength, by static tests.

(ii) Behaviour of beams when subjected to pulsating load with regard to free end slip of strand.

(iii) Determination of ultimate bond strength of strand by static test of beam after subjecting them to pulsating loads upto about one million cycles.

(iv) Comparision between static flexural bond strength and post pulsating bond strength.

(v) Determination of load-deflection, defection - cycle behaviour during beam tests under static and pulsating load conditions.

(vi) Effect of secondary anchorage on static and pulsating loads.

In the present investigation, bond studies are done on untensioned strands. It is assumed that once the general slip occurs, the frictional resistance, in the transfer zone, which is caused by the radial pressure (Hoyer effect), is reduced and mechanical resistance on the helical surface is the main factor which contributes to bond between concrete and the strand. The bond behaviour of tensioned strand would be better when compared with untensioned strand because of Hoyer effect in the transfer zone. The untensioned strands would, thus, give conservative values.

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# CHAPTER II

# PULL - OUT TEST

## 2.1 : INTRODUCTION:

One of the aims of this investigation is to determine the bond behaviour of seven-wire strand under static and pulsating load conditions. In beam test, embedment length is to be varied and for this, a primary knowledge on the average bond length is required. To get an idea about the bond strength, some preliminary tests had to be carried out and for this the easiest would be a simple pull-out test. Pull-out test results would give an idea about the average bond strength that could be used in designing strands as bonded reinforcement for lifting handles, junction connectors, etc. It is also helpful in understanding the bond behaviour of strand under simple tension.

For preliminary test, the following experiments were conducted:

(i) Tensile strength of strand.

(ii) Pull-out test.

## 2.2 : TEST SPECIMEN:

### 2.2.1 Testing of Strand:

The strand used for the entire investigation was a seven-wire strand with nominal diameter of 6.35 mm. Two specimens, of gauge length 194 mm and 203 mm, were taken and the tensile strengths of

the strands were determined by Instron, tensile testing machine, which plotted the load versus strain automatically. The stress-strain curve of one specimen is given in Fig. 2.1.

2.2.2 : Pull-out specimen:

15 pull-out specimens with varying bond length as detailed below were used

| Bond length | Number of specimens |
|---|---|
| 95 diameter | 3 |
| 118 diameter | 6 |
| 140 diameter | 6 |

The details of pull-out specimens and the moulds used for casting the specimens are shown in Fig.2.2.

The mould to cast these specimens consisted of 3 wooden platforms on which two specimens were cast. To this wooden platform 3 cast iron cylinders, the ones used for cylinder tests, were fixed one over another with the help of two 10 mm rods. At the centre of this cylindrical arrangement, a hole was drilled in the wooden platform so as to pass a nut, which was welded to the strand to faciliate the fixing of dial gauge while carrying out the pull-out test. On the top of this arrangement, a frame was clamped to the cylinder, so as to keep the strand, as far as possible, straight with the help of spring arrangement. The details of this arrangement is shown in Fig.2.2. To provide a bonded length of 95 diameters, just two cylinders

were sufficient. For providing 140 ∅ bonded length, all the three cylinders were used and for 118 ∅ bonded length specimen, three cylinders were used and the strand was covered with a polythene tube for a portion so as to give the required bonded length. Spiral reinforcement made from 6 mm ∅ bar was provided in the pull-out specimen at a pitch of 30 mm for a distance of 300 mm from the top. This was provided so as to avoid any tensile cracks while carrying out the pull-out test.

2.2.3: Basic Materials:

The specimens were cast with concrete consisting of 12 mm and 20 mm coarse granite aggregate and Kalpi Sand of F.M. = 2.7 and Puzzolana cement. Concrete mix of 1:0.9: 1.9, by weight, was used with an average water cement ratio of 0.39.

## 2.3: CASTING AND CURING:

### 2.3.1: Casting of Specimen:

Two moulds were fixed on one platform. This entire set was put on two levelled steel girders so as to give some working space below the specimen. The inside of the mould was oiled and the strand and helical reinforcement inserted. The strand was adjusted and given slight tension, so as to keep it straight and in the centre of the mould.

The quantity of concrete for three specimens was mixed each time. The concrete was poured in the mould in different layers

and carefully vibrated with the help of a needle vibrator to ensure good compaction. The moulds were opened and removed after twenty four hours.

With this arrangement of mould for the pull-out specimens, the maximum bond length provided was 140 $\phi$ . For reasons of keeping the strand straight and compaction, it would have been difficult to go for bond lengths more than 140 $\phi$ .

2.3.2: Cement Concrete Cubes:

For each batch of pull-out specimens, at least three cubes of 150 mm size were cast alongwith with the casting of pull-out specimens. The cubes had been compared by the needle vibrator.

2.3.3: Curing:

Pull-out and cube moulds were opened after twenty four hours of casting and the specimen and cubes were put in water till the time of testing.

## 2.4: TEST SET-UP AND INSTRUMENTATION:

Pull-out test was performed on a universal testing machine. The specimen was kept on the top of the fixed cross head with the strand projecting down through the hole of the cross head. A plywood sheet, 3 mm thick, was provided between the specimen and the top of cross head for uniform seating of the specimen when under load. The projected end of the strand was gripped in the moving head such that a distance of 200 mm was maintained between the fixed head and the moving head.

The free end slip of the strand was measured with the help of a dial gauge, the top of which rested over a nut, which was welded to the top of the strand projecting from the specimen. The dial gauge was fixed to a steel frame attached to the body of the pull-out specimen by means of screws. The arrangement provided direct measurement of the free end slip indicated by the gauge readings. The pull to the strand was applied by the movement of the lower cross head.

## 2.5 : TESTING PROCEDURE:

### 2.5.1 : Tensile test of strand:

Seven-wire strand of 6.35 mm nominal diameter, the properties of which are given in Table 1.2, was used for the entire investigation. The tensile specimens were tested by Instron, tensile testing machine. The strand was gripped to the jaws of the machine and it was ensured that the strand did not slip from the jaws when the load was applied. Two specimens of gauge length 203 mm and 194 mm were tested. The cross-head speed was adjusted to 1 mm/min. The load versus extension is automatically plotted by the machine, for which the chart speed was maintained at 20 mm/min. The result of the test in form of load-strain curve is shown in Fig.2.1 and tabulated in Table 2.1.

### 2.52: Compressive strength of concrete cubes:

Compressive test on 150 mm size cubes was done by compression testing machine on the day of the testing of the specimen of pull-out test of the same mixture. The cubes were placed between platens of the machine and a gradually increasing load was applied. The ultimate load was noted. The cube test results are given in Table 2.2.

### 2.5.3: Pull-out Test:

The pull-out specimen was fixed to the universal testing machine as described in section 2.4. The dial gauge frame was then fixed to the specimen, with the help of bolts, to which the gauge was fixed and adjusted to give the free end slip. Pull was slowly applied and the load corresponding to the first slip was noted. The load was subsequently increased in intervals of 100 kg. and the slip readings were taken at each interval and the ultimate load was noted. The summary of pull-out test results are given in Table 2.3 and the bond stress versus free end slip curves are plotted in Figures 2.3, 2.4 and 2.5. The bond stress versus bond length is given in Fig. 2.6.

## 2.6 : OBSERVATION ON PULL-OUT TEST:

(i) Even after the general bond slip, there is a lot of stress transfer capacity in the specimen, which is evident from the bond versus slip curves for the three types of specimens.

(ii) In all the pull-out tests, the failure was due to bond slip and there was no cracking in any of the specimens.

(iii) Ultimate bond stress has an increasing tendency with decrease in embedment length.

## 2.7 : CONCLUSIONS:

(i) Stress transfer occurs upto a slip of more than 7 mm.

(ii) The ultimate bond strength decreases with increase in the embedment length till the full bond length is embedded (Fig.2.7).

(iii) After the initial free end slip, a non-linear load slip curve is obtained.

---

TABLE 2.1 : TENSILE TEST OF STRAND

| S.No. | Maximum tensile load kN | Ultimate tensile stress MPa | Proof stress at 1% Residual strain MPa |
|---|---|---|---|
| 1 | 43.0 | 1851.8 | 1705.4 |
| 2 | 43.25 | 1862.6 | 1705.4 |

TABLE 2.2: CUBE STRENGTH OF CONCRETE

| Mix.No. | Date of casting | Date of Testing | Average cube strength | Standard Deviation |
|---|---|---|---|---|
| I | 18.2.81 | 23.3.81 | 32.0 | 0.9 |
| II | 19.2.81 | 24.3.81 | 32.5 | 1.02 |
| III | 20.2.81 | 25.3.81 | 30.2 | 0.8 |
| IV | 20.2.81 | 25.3.81 | 31.5 | 1.11 |
| V | 21.2.81 | 26.3.81 | 30.5 | 1.21 |

TABLE : 2.3: PULL OUT TEST WITH BONDED LENGTH 95 DIAMETERS

| Specimen Designation | Average Cube Strength | Load at general bond slip | Ultimate Load | Bond stress at initial Bond slip | Ultimate Bond strength |
|---|---|---|---|---|---|
| | MPa | kN | kN | MPa | MPa |
| $S_1$ | .. | 30.5 | 31.6 | 2.534 | 2.626 |
| $S_2$ | 32.0 Mix-I | 31.5 | 33.0 | 2.618 | 2.742 |
| $S_3$ | | 18.0 | 29.0 | 1.495 | 2.41 |

TABLE 2.4: PULL OUT TEST WITH BONDED LENGTH 118 DIAMETER

| Specimen designation | Average cube strength | Load at general bond slip | Ultimate Load | Bond stress at initial Bond slip | Ultimate Bond stress |
|---|---|---|---|---|---|
| | MPa | kN | kN | MPa | MPa |
| $S_1$ | 31.5 | 17.0 | 25.0 | 1.137 | 1.673 |
| $S_2$ | Mix-IV | 30.0 | 35.5 | 2.007 | 2.373 |
| $S_3$ | | 27.0 | 37.75 | 1.806 | 2.526 |
| $S_4$ | | 20.0 | 36.0 | 1.338 | 2.408 |
| $S_5$ | 30.5 | 15.0 | 25.0 | 1.004 | 1.676 |
| $S_6$ | Mix-V | 23.0 | 38.25 | 1.539 | 2.559 |

TABLE 2.5: PULL OUT TEST WITH BOND LENGTH 140 DIAMETERS

| Specimen Designation | Average cube strength | Lead at initial bond slip | Ultimate Load | Bond stress initial Bond slip | Bond strength |
|---|---|---|---|---|---|
| | MPa | kN | kN | MPa | MPa |
| $S_1$ | 32.5 | 27.0 | 36.0 | 1.523 | 2.03 |
| $S_2$ | Mix-II | 23.0 | 37.5 | 1.297 | 2.12 |
| $S_3$ | | 23.5 | 39.75 | 1.325 | 2.242 |
| $S_4$ | 30.2 | 32.0 | 35.75 | 1.805 | 2.016 |
| $S_5$ | Mix-III | 22.5 | 29.5 | 1.27 | 1.665 |
| $S_6$ | | 19.0 | 33.0 | 1.073 | 1.861 |

TABLE 2.6: AVERAGE VALUE OF BOND STRESS BY PULL OUT TEST

| S.No. | Bonded Length (Dia.) | No. of Specimen | Average value of Bond stress at initial bond slip | Bond strength |
|---|---|---|---|---|
| | | | MPa | MPa |
| 1 | 95 | 3 | 2.21 | 2.592 |
| 2 | 118 | 6 | 1.471 | 2.202 |
| 3 | 140 | 6 | 1.382 | 1.99 |

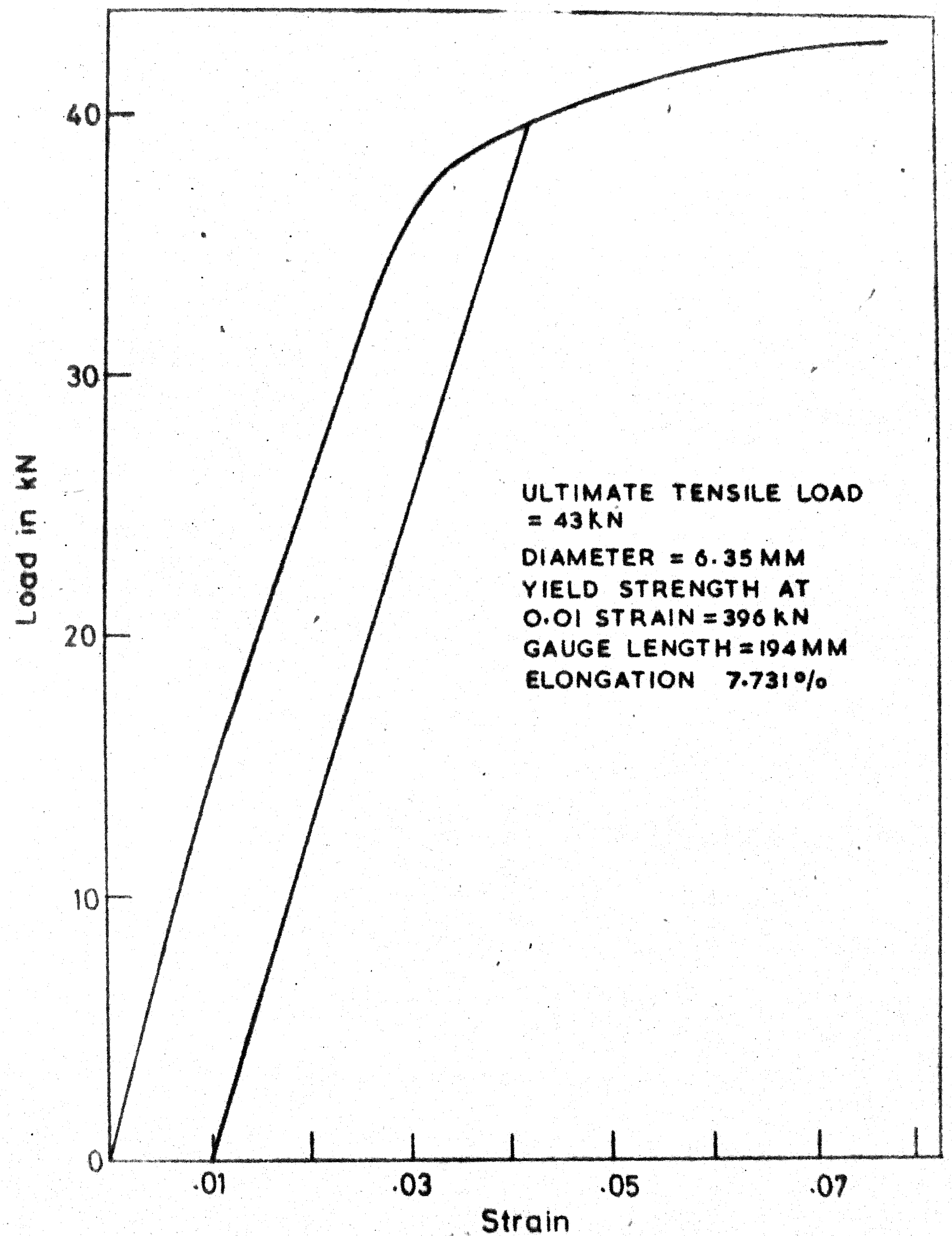



FIG. 2.1 STRESS STRAIN CURVE OF SEVEN-WIRE STRAND OF 6.35 mm DIA.

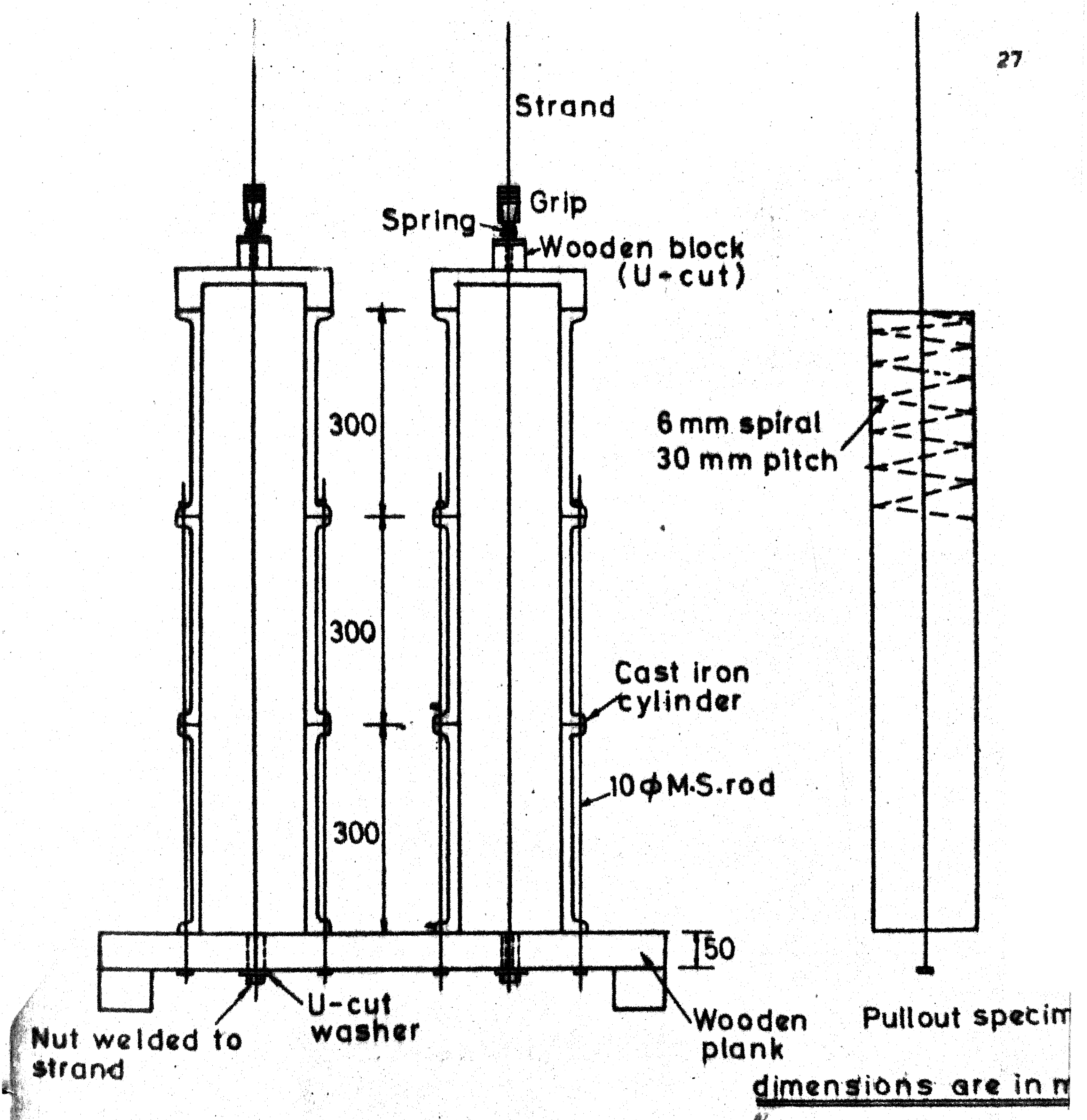



FIG. 2.2 DETAILS OF MOULD FOR PULL OUT SPECIMEN

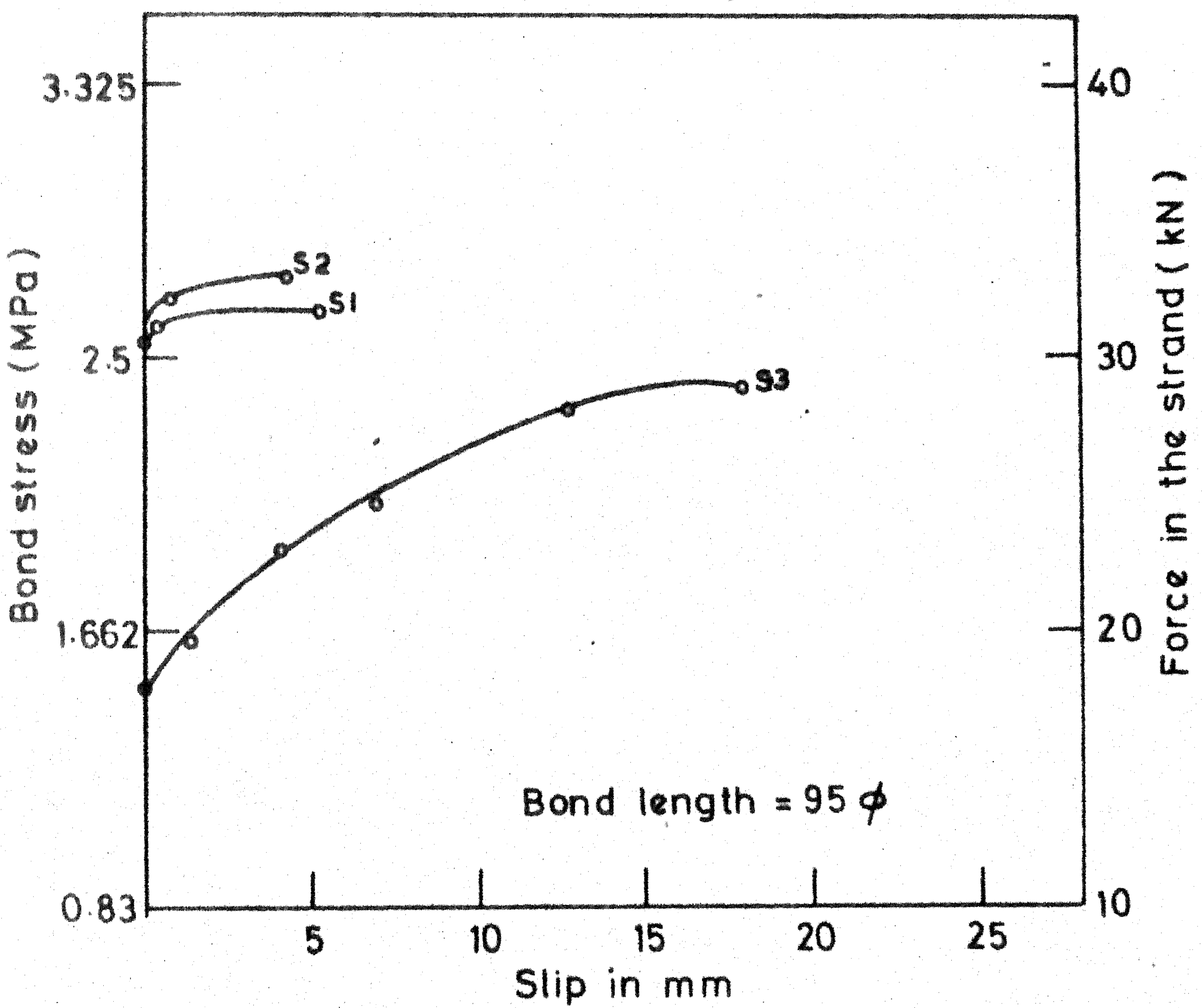



FIG. 2.3 BOND STRESS VS. SLIP

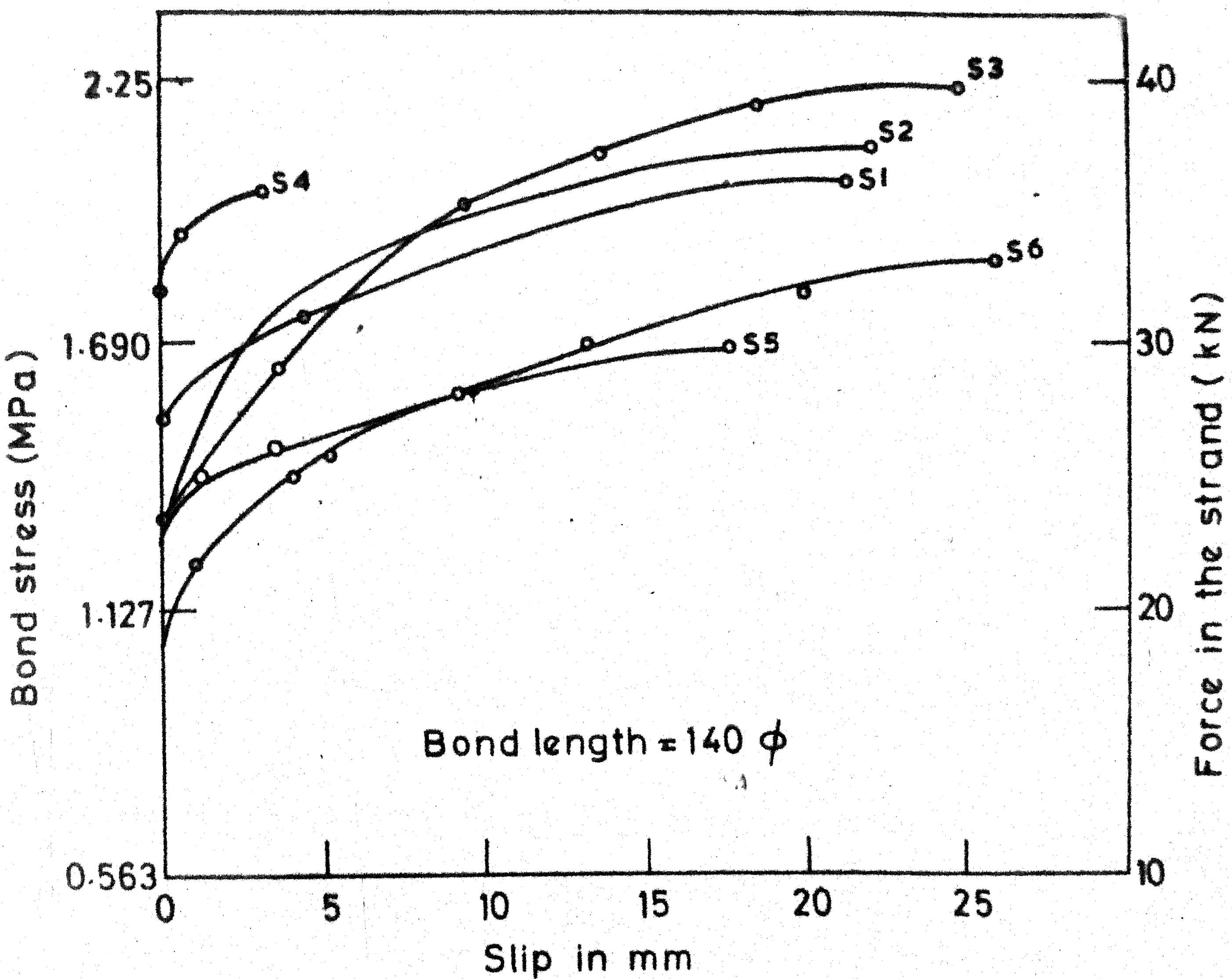



FIG. 2.5 BONDSTRESS VS. SLIP

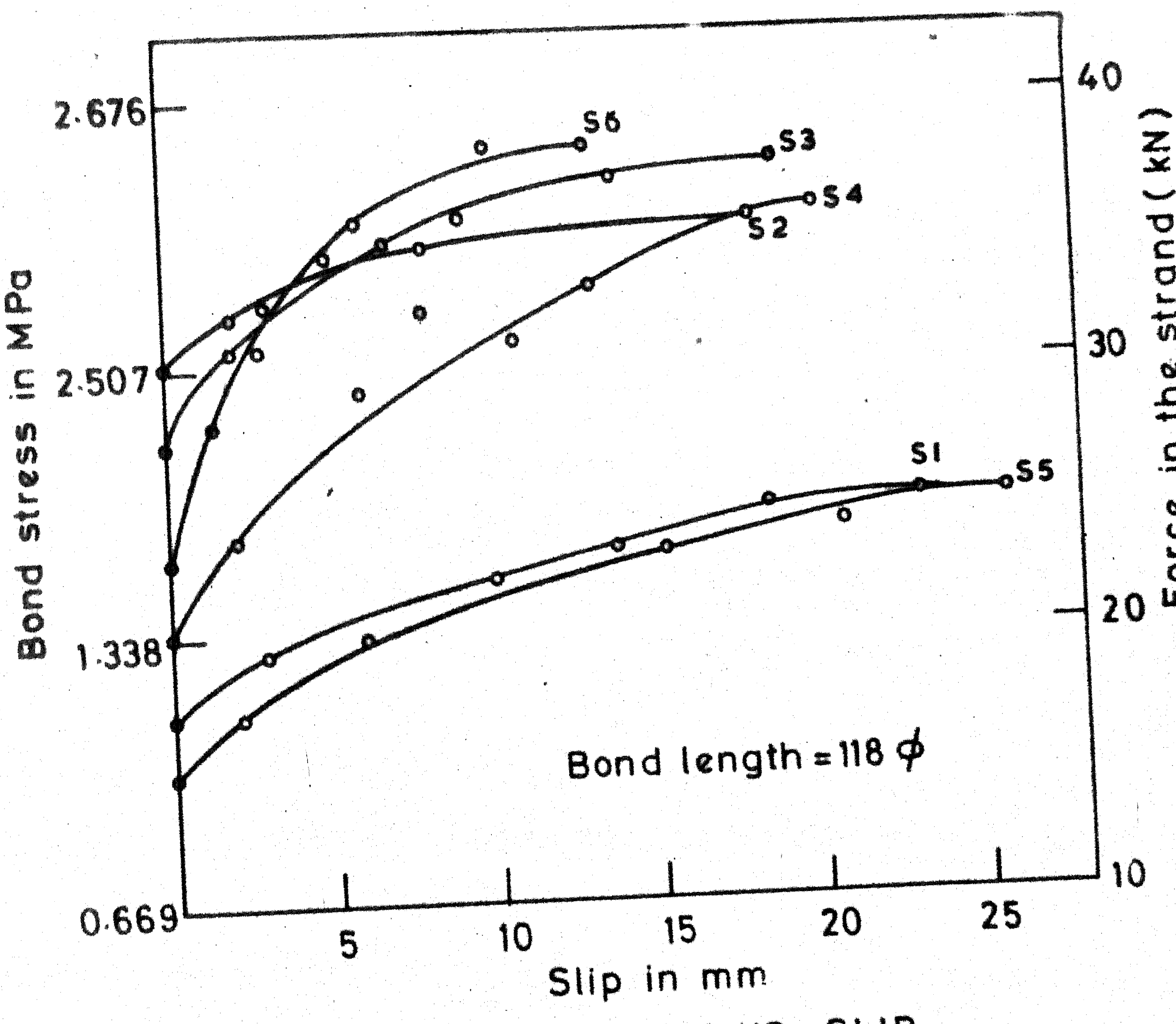



FIG. 2.4 BOND STRESS VS. SLIP

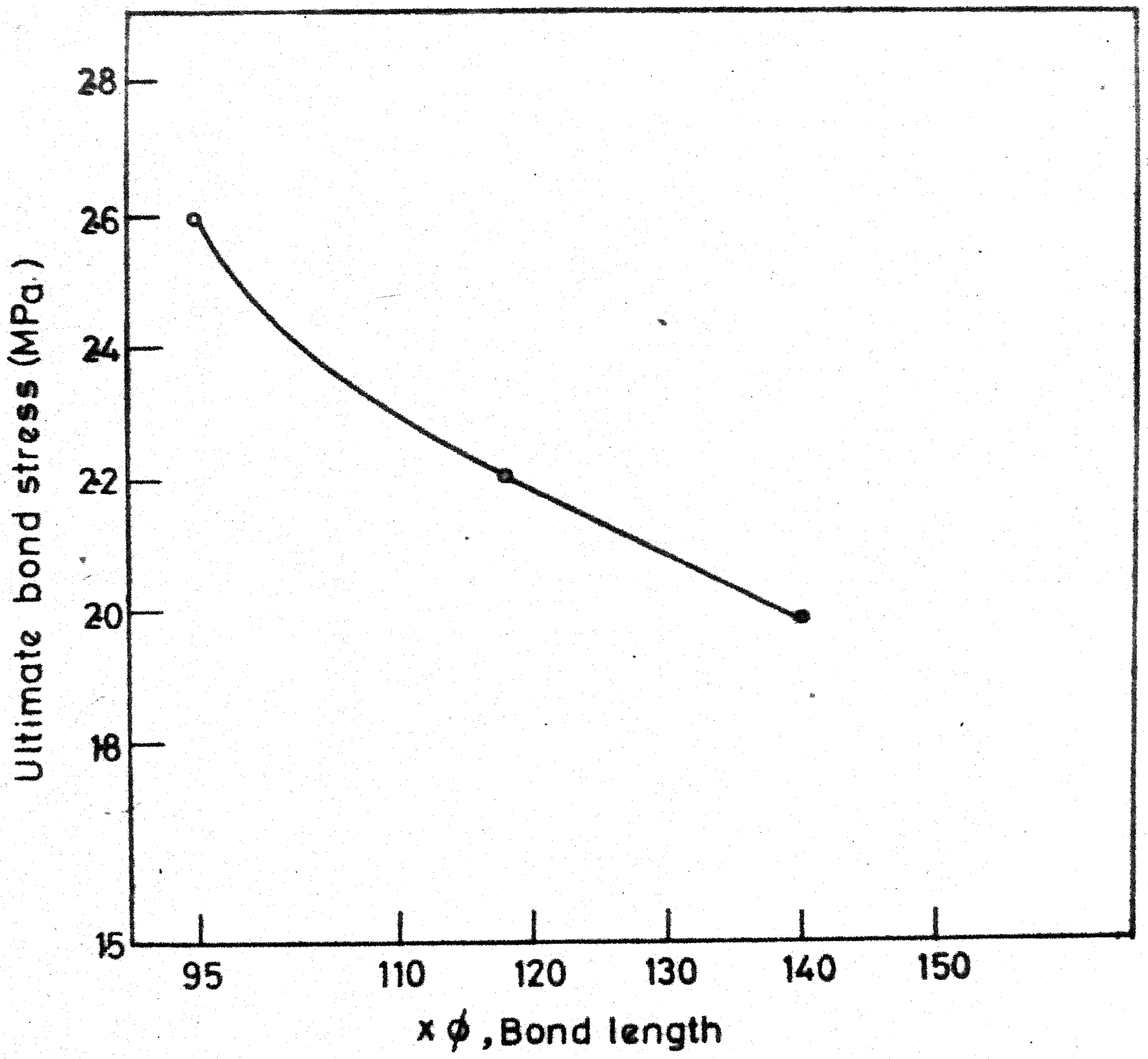



FIG. 2·6 ULTIMATE BOND STRESS VS. BOND LENGTH FOR PULL OUT TESTS.

# CHAPTER III

## EXPERIMENTAL PROGRAMME

### 3.1 : INTRODUCTION:

The main purpose of the present experimental investigation was to study the bond behaviour under pusleting load for strands, which developed only a partial bond ( or partial slip ) due to constructional problems. Also, to improve the bond-cum-anchorage behaviour of such strands, a secondary anchorage device is used and studied.

Since the study is done for a strand which has developed partial bond because of which the bond length may vary, different bonded lengths were chosen. For this investigation, two sets of beams having bonded lengths of 150 ∅ and 175 ∅ without secondary anchorage were chosen. For studying the effect of secondary anchorage, a low embedded length of 140 ∅ was chosen.

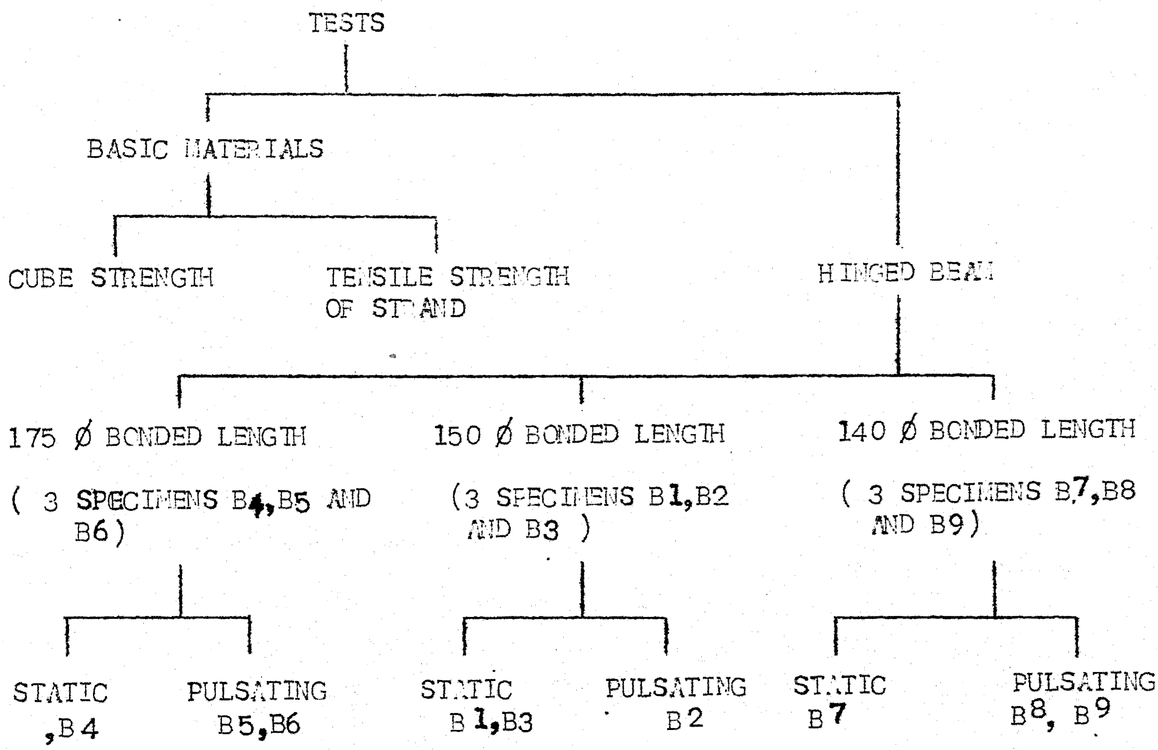
### 3.2 : LIST OF TESTS:

Three sets with different embedded lengths, i.e, nine beams, in all, were tested. The list of tests is given on page 33.

### 3.3: TEST SPECIMEN:

3.3.1 Design of the specimen:

There were nine beams, singly reinforced, 80 x 200 mm in section and each was reinforced with one seven-wire strand of 6.35 mm diameter. At the mid span of the beam a mechanical hinge, shown in Fig. 3.2, was fixed. This consisted of two V-blocks to hold a roller of 24 mm diameter and length equal to the width of the beam. The thick-


TESTS
BASIC MATERIALS
CUBE STRENGTH
TENSILE STRENGTH OF STRAND
HINGED BEAM
175 Ø BONDED LENGTH
( 3 SPECIMENS B4,B5 AND B6)
150 Ø BONDED LENGTH
(3 SPECIMENS B1,B2 AND B3 )
140 Ø BONDED LENGTH
( 3 SPECIMENS B7,B8 AND B9)
STATIC ,B4
PULSATING B5,B6
STATIC B1,B3
PULSATING B2
STATIC B7
PULSATING B8, B9

ness of beam section at mid span was kept as 50 mm so that it did not fail under compression due to the ultimate moment at that point. The projection of the strand at the two ends was kept about 35 mm and a steel plate 30 x 20 mm was welded at the two ends of the strand, so as to faciliate placing of dial gauges for slip measurement. The total length of the beam was 3500 mm and the effective span was 3270 mm. Shear reinforcement, in the form of two 10 mm bars with 6 mm stirrups at a spacing of 150 mm, was also provided. Details of the specimens and their reinforcements are shown in Fig.3.1. The details of the design is given in Appendix A.

3.3.2 : Basic Materials :

The specimens were cast with concrete consisting of 20mm and 12mm size coarse aggregates, Kalpi sand with a F.M. of 2.7 and Puzzolana cement. Concrete mix used was 1:0.9:1.9 by weight, with an average water-cement ratio of 0.38. For each specimen, six 150 mm cubes were cast, three of which were tested after 28 days, while the other three were tested on the day, the beam test was started as given in Table 3.1. The average cube strength for different specimen was as is given in Table 3.1.

## 3.4 : CASTING AND CURING:

3.4.1 : Making of moulds:

For casting the beam specimen, two wooden moulds were made as shown in Fig.3.5. The vertical sides of the mould were connected with the horizontal sides by means of pocket screws, so that they can be

easily detached. The two wooden end-pieces had a horizontal cut with a central hole, in each, to enable the strand to pass. The lower piece was fixed to the mould with the help of screws. The horizontal cut was necessary in removing the specimen easily.

3.4.2 : Making of hinge:

The hinge arrangement consisted of two V blocks and 24 mm diameter roller holes were made in the V-blocks to fix them onto the struts embedded in the specimen. The hinge arrangement is as shown in Figures 3.2, 3.3 and 3.4.

3.4.3 : Casting of the Specimen:

The beam specimen was cast in an inverted position, so as to facilitate in the placing of concrete and positioning of the strand. The inner surface of the mould was well oiled. The strand to be used in the beam was cut to size and cleaned. Before welding the two steel plates at the two ends, polythene tube of required length was pulled over the strand so as to give the required bonded length.

Two holes, on each plate (of thickness 5 mm) of size 78 mm x 50 mm, were drilled and two struts, on each plate, were welded as shown in Figure 3.3. The mould was kept on a levelled platform. Grease was applied on the surface of the roller and the V-blocks. The hinge arrangement, fixed with a plate on either side, was kept in proper position and then shear reinforcement was positioned. Materials were mixed in one batch for one specimen for about 8 minutes. The concrete

was placed in the moulds in small quantities and thoroughly vibrated with a needle vibrator. Control specimens consisting of six 150 mm cubes were cast simultaneously. The top surface of the specimen and the cubes were made level and an identification mark was given.

3.4.4 : Secondary Anchorage:

For beams $B_7$, $B_8$ and $B_9$ secondary anchorage system was provided as shown in Figure 3.6. This consisted of a 3 mm thick steel plate with a nut welded to the projecting free end of the strand at each end of each beam.

3.4.5 : Curing:

After 24 hours of casting, the specimen was taken out from the mould and was placed for curing. The hinge arrangement was taken out from the specimen leaving the plates with struts embedded in the concrete. Then the specimen was covered with damp gunny bags. The gunny bags were kept damp for 27 days. The control cubes were also cured under similar conditions. Casting schedule, specimen designation and cube test results are given in Table 3.1.

## 3.5: TEST SET UP AND INSTRUMENTATION:

3.5.1 : Test Set up:

The general arrangement of the test set-up is shown in Figure 3.7. The dimensional details of the test set-up are given in Figure 3.7. The specimen was tested as a beam, supported on roller bearings. The effective span for all the specimens was 3270 mm. One end

of the specimen was a hinged support and the other was a simple roller support in order to allow horizontal movement of the specimen along that direction. Two point loading was applied to the beam with the help of 40 kN (4 ton) jack monitored by a pulsator. The jack was fixed to the test frame, the test frame being securely fixed to the structure floor. Loading was attained through a reaction girder and was applied to the beam through two steel rollers of 40 mm diameter. These rollers rested over a 5 mm plate which, in turn, were fixed to the beam with the help of plaster of paris. In order to prevent undesirable vibrations of the test frame, four tie rods were provided and were tightened frequently to arrest vibrations, if any.

3.5.2 : Instrumentation:

The free end slip was measured with the help of a dial gauge, the tip of which touched the surface of the steel plate, welded to the strand projecting from the specimen. The dial gauge was fixed to the steel frame, which, in turn, was attached to the specimen by means of four screws. This sort of arrangement, used for static as well as dynamic tests, provided direct measurement of free end slip as indicated by the gauge readings.

For measurement of vertical displacementof the beam, two dial gauges were fixed at a distance of 720 mm from the supports. Fixing of dial gauge at the centre was not possible as the deflection was large. The distance between the centre of the hinge and centre of the strand was measured with the help of a steel scale.

## 3.6: TESTING PROCEDURE:

### 3.6.1 : Testing Programme:

Static as well as pulsating loads were applied through a 40 kN (4 ton) jack monitored by a pulsator unit.

There were three sets of beams with three in each set. The bonded lengths provided for the three sets were 175 Ø , 150 Ø and 140 Ø + secondary anchorage.

Two beams from set one and one each from second and third sets were tested for static ultimate strength under monotonically increasing load. The remaining specimens were subjected to a loading programme which is as summarized below:

(1) Two to three cycles of static loading before the start of the pulsating load programme.

(2) Pulsating load programme - loads varying between a lower limit and an upper limit.

(3) Sustained loading slightly less than the upper limit.

(4) One cycle of static loading, monotorically increasing upto failure, as a post-pulsating load programme.

### 3.6.2: Selection of Loads:

For determining the upper and lower load limits, static test on one of the specimens from a given set was conducted. The ultimate bond strength of the beam and behaviour of the slip was noted. A load slightly less than the load that would start the initial free end slip in the static beam was selected as the upper load limit. The lower load

limit was fixed by taking into consideration the pulsator constraints, the range of load fluctuation and the stability of the specimen.

3.6.3: Static and Pulsating load test:

Specimens B1, B3, B4 and B7 were subjected to static load while B2, B5, B6, B8 and B9 were subjected to pulsating load. The upper and lower load limits for different beams is given in Table 4.3.

(a) STATIC TEST:

The necessary instrumentation was done after placing the specimen in proper position and an initial load of 2% of jack capacity was applied and then released to zero. After some time, zero reference of the dial gauge readings and the distance between roller and the strand were recorded. Then the load was applied with increments of 2% of the jack capacity. At each increment, the dial gauge readings, for determining free end slip and vertical deflections, were taken. The load was increased until the beam ultimately failed.

(b) PRE-PULSATING LOAD TEST:

The specimens were monotonically loaded upto the upper load limit, which was determined by static load test as described in section 3.6.2. The load was then released at interval of 2% of the jack capacity to zero and readings for deflection and free end slip, if any, were taken. This cycle was repeated again, then the load was again increased upto the upper load limit after which pulsating load was applied.

(c) SUSTAINED LOADING:

A load slightly less than the upper load limit was applied for about ten minutes and the free end slip was noted.

(d) PULSATING AND POST-PULSATING TEST:

Pulsating load on different specimens in the form of upper and lower load limits, were applied at an average frequency of 400 cycles per minute for 6 to 7 hours a day. The load levels for different specimens were released of all external loads for about 16 hours. This type of loading was continued for about one million cycles and the amount and behaviour of slip noted. The fatigue effect produced by accelerated fequency was minimized by allowing a relaxation in loading for 16 hours.

After application of one million cycles of load, monotonically increasing static load was applied to the specimen uptill failure and the deflection and the slip were noted.

TABLE 3.1: SPECIMEN DETAIL, CASTING SCHEDULE AND CUBE RESULTS

| S. No. | End secondary anchorage | specimen No. | Bonded length | Date of casting | Date of testing | 28 days average cube strength MPa | Age on test data (days) | Average cube compressive strength on that date MPa |
|---|---|---|---|---|---|---|---|---|
| 1 | | B1 | | 13.3.81 | 24.4.81 | 28.9 | 42 | 32.1 |
| 2 | NO | B2 | 150 ø | 16.3.81 | 27.4.81 | 29.0 | 42 | 31.5 |
| 3 | | B3 | | 18.3.81 | 28.4.81 | 30.6 | 41 | 32.0 |
| 4 | | B4 | | 27.3.81 | 29.4.81 | 29.7 | 33 | 31.0 |
| 5 | NO | B5 | 175 ø | 27.3.81 | 1.5.81 | 30.5 | 35 | 31.5 |
| 6 | | B6 | | 6.4.81 | 13.5.81 | 30.8 | 37 | 31.7 |
| 7 | | B7 | | 6.4.81 | 22.5.81 | 29.8 | 46 | 32.3 |
| 8 | Yes | B8 | 140 ø | 13.4.81 | 20.5.81 | 30.8 | 37 | 32.1 |
| 9 | | B9 | | 16.4.81 | 2.6.81 | 30.0 | 47 | 31.5 |

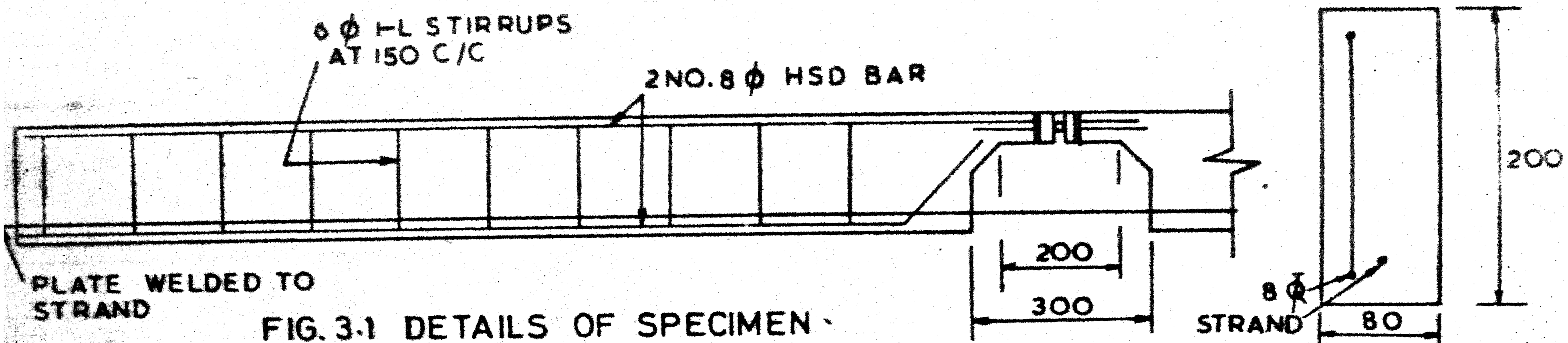



FIG. 3.1 DETAILS OF SPECIMEN

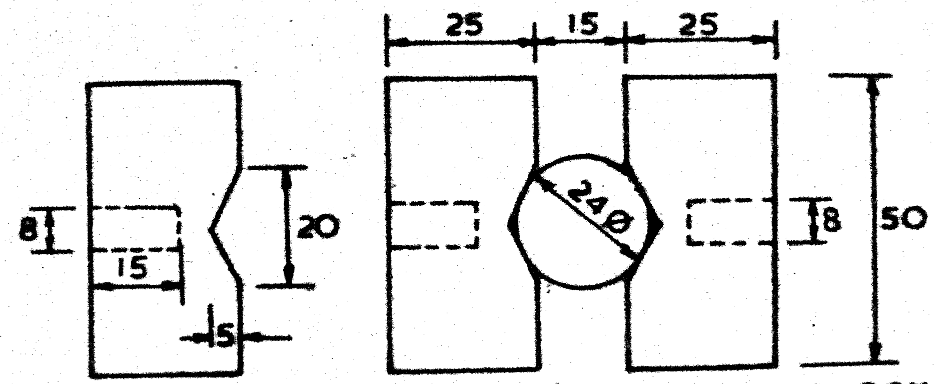



FIG. 3.2 V-BLOCK AND HINGE

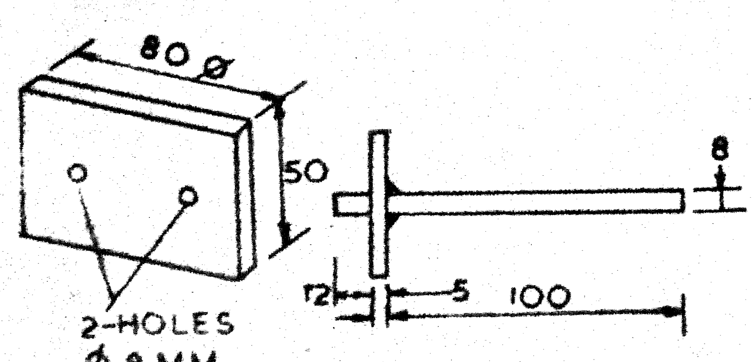



FIG 3.3 PLATE WITH STRUTS

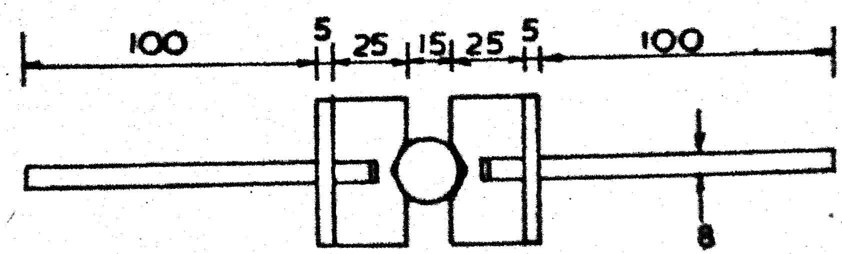
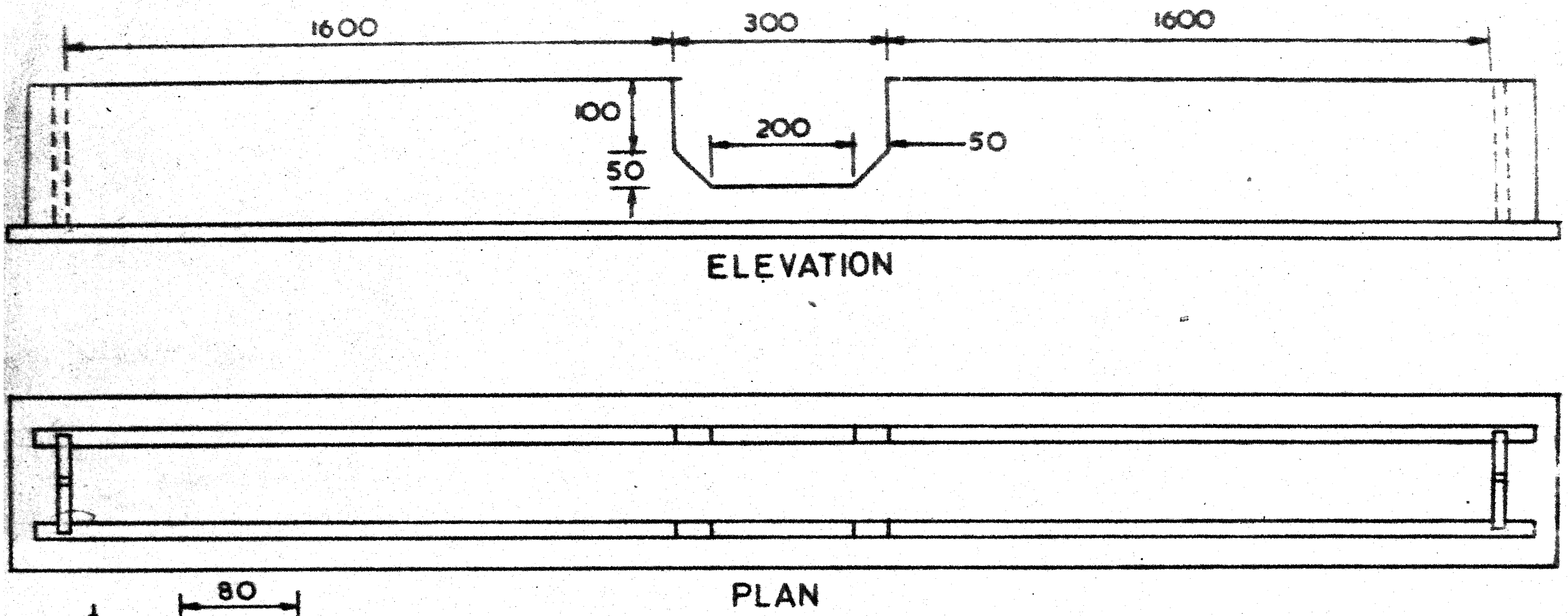



FIG. 3.4 TOTAL HINGE ARRANGEMENT

ALL DIMENSIONS IN MM



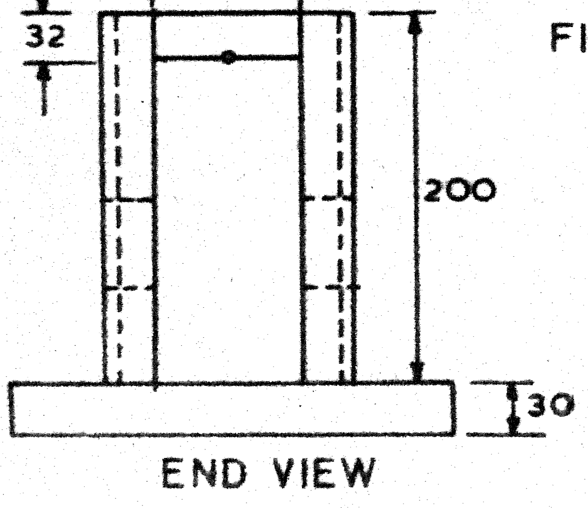




FIG. 3.5 DETAILS OF MOULD FOR BEAM SPECIMEN

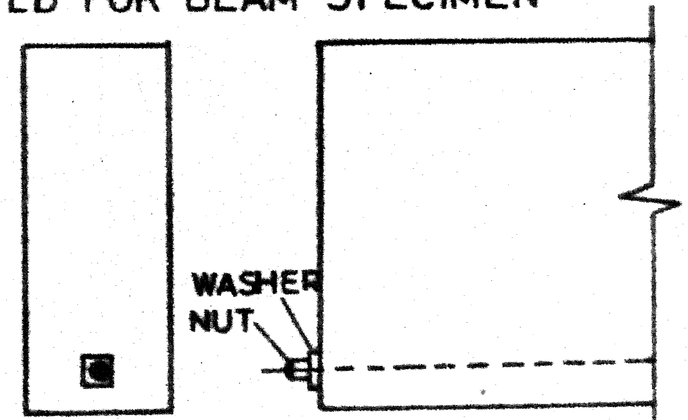



FIG. 3.6 SECONDARY ANCHORAGE

ALL DIMENSION IN MM

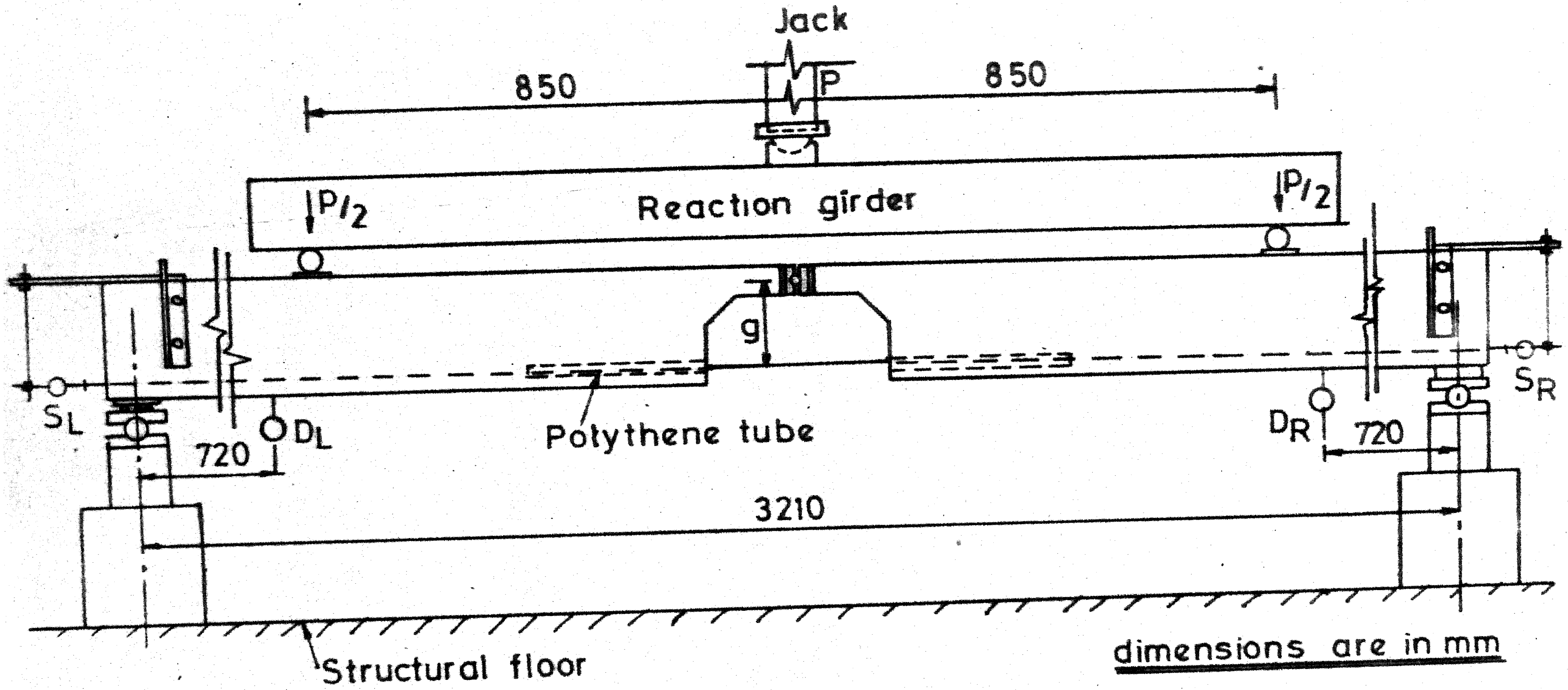



FIG. 3.7 DETAILS OF BEAM TEST SPECIMEN AND TEST SET-UP

# CHAPTER - IV

# OBSERVATIONS AND DISCUSSIONS

## 4.1: INTRODUCTION:

During the entire investigation, three types of tests viz., (i) Pull out test (ii) Beam tests, with and without secondary anchorage, under static load and (iii) Beam tests, with and without secondary anchorage under pulsating loads, were under taken to study the bond behaviour of seven-wire strands. Pull-out tests were done for different embedment lengths and so were the beam tests under static and pulsating load conditions. The loading conditions for these tests were different. In this chapter, the bond behaviour of seven-wire strands has been studied with regard to different tests under taken.

## 4.2: Pull-out tests:

Pull-out tests were done for three sets of embedment lengths viz., 95 Ø, 118 Ø and 140 Ø. Initial bond slip at free end, increase in load with slip and ultimate loads were observed for all the specimens.

The average bond strength at initial slip and ultimate slip are given in Table 4.1. Even after initial free end slip, an increase in bond strength was exhibited. Strands subjected to gradually applied load produce a non-linear load-slip curve after the initial free end slip. The helical surface of the strand provides some mechanical interlocking. Also, as the strand elongates, the pitch of the strand

changes with respect to the surrounding impression on the concrete, thus, causing increased normal and frictional forces which more than compensate for the effect of radial contribution associated with the elongation of the strand. When the strand is unloaded the frictional forces reverse themselves, thus, producing permanent deformation. Because of this, there was no recovery in the free end slip.

From Fig.2. 6 , a plot between bond strength and embedment length, it is clear that ultimate bond strength decreases with increase in embedment length. This is due to the fact that in pull-out test a high bond stress is developed near the pulling ends, which gradually reduces to zero at the free end for longer embedment lenths while for shorter embedment lengths this decrease is not that gradual. Thus shorter embedment lengths show higher average bond strength as compared to average bond strength of longer embedment lengths.

A lower bond relationship between embedment length and stress in steel at initial free end slip, from Fig. 4.1, is derived and is as follows.

$$\sigma_s = 1.2\, L_e - 240 \qquad (4.1)$$

where $\sigma_s$ is the limit of stress in steel based on slip in $N/mm^2$ and $L_e$ is the embedment length of strand in mm.

The above equation can be used for selecting an embedment length required for a particular strand, when embeded straight, under untensioned condition. The initial free end slip condition provides a

conservative lower bound estimate for the ultimate capacity of embedded untensioned strand.

4.3: Static Test on Beams:

So as to select the upper load for pulsating tests and to compare the ultimate capacities after pulsating, it was necessary to conduct the static tests. In the first set, three beams having bonded length of 150 Ø , two beams, B1 and B3, were tested under static load conditions. Both the specimens failed by bond slip. The stress in the strand, for the two beams, at initial free end slip was 51 and 52.4% of the proof stress while at total slip failure the stress in the strand was nearly equal to the proof stress. The maximum slip was 6mm and 6.4mm, respectively.

Beams B4 and B7 from set two and set three were also tested under static loads. B4, having a bonded length of 175 Ø, failed by bond slip, the initial free end slip taking place when the stress in the strand was 59% of proof stress with corresponding bond stress as 1.05MPa. At the ultimate slip the stress in the strand was nearly equal to the ultimate stress of the strand, the bond strength being 1.8 times the initial bond stress. Beam B7 had a bonded length of 140 Ø and was provided with secondary anchorage. In this case, the failures was due to yielding of the strand.

Table 4.2 gives a critical review of ultimate bond capacities of beam specimens and its relation with intital free end slip. Bond stress vs. free end slip are plotted in Fig.4.2 and Fig.4.3 and load -

deflection curves for B1 and B2 are plotted in Fig.4.4.

4.4: Pulsating Load Test:

In pulsating load test, upper load was taken slightly less than the load which caused the initial free end slip in static load tests. The lower load was chosen after taking into account the machine and load fluctuation constraints. It was proposed to subject the beam to one million cycles in order to study the bond behaviour.

In the first set, with bonded length of 150 Ø, one beam, B2, was tested under pulsating loads keeping upper load causing bond stress as 1.15 MPa and lower load causing a bond stress as 0.86 MPa, while the corresponding stress in the strand was 55 and 42% of the proof stress. In about 25000 cycles the free end slip on the right end was 10.4mm and the pulsating loads were stopped, the beam, was then, tested for ultimate strength.

Of the second set having three beams with bonded length of 175 Ø, two beams, B5 and B6, were tested under pulsating loads. The upper and lower loads were chosen so as to give a bond stress of 1.1 MPa and 0.76 MPa, respectively. The corresponding stress in the strand was 56 and 42% of the proof stress. The beams were subjected upto one million cycles and the free end slip, central deflection and recovery were observed.

The third set, having a bonded length of 140 Ø was provided with a secondary anchorage at the two free ends. Two beams, B8 and B9, were tested under pulsating loads. The stresses in the strand for upper and lower loads were 68% and 52% of the proof stress.

The details of the pulsating tests are given in Table 4.3. Free end slip vs. number of cycles curves are shown in Fig.4.7 and Fig.4.12. While the cumulative central deflection vs number of cycles are shown in Fig.4.8 to Fig.4.12.

4.5 : Post - Pulsating Tests:

All beams subjected to pulsating tests were tested for ultimate strength. The test results for these beams are plotted as bond stress vs free end slip and are given in Fig.4.13 to Fig.4.15 and plots of jack load Vs central deflection are given in Fig.4.16 to Fig.4.20.

The stresses in the strands at failure under static load test came out to be 1712 MPa, 1808 MPa and 1805 MPa respectively for beams with bonded lengths 150 Ø, 175 Ø and 140 Ø with secondary anchorage. Bond stress and the stress in the stand at upper and lower load limits are given in Table 4.3.

It can be seen, for sets one and two, from the bond stress vs free end slip curves and Jack load vs deflection curves, that due to the application of load cycles, the ultimate bond capacity and hence the ultimate capacity of the beam tend to decrease. Also, it has been found that due to pulsating load, the strand has acquired a permanent

free end slip from zero load to upper load. There is no recovery of this slip when the load is brought down to zero.

It was observed that the free end slip under pulsating load took place in jerks and was not continuous. During post-pulsating static load the strand reveals some stress - transfer capacity although the rate of increase in the free end slip is quite rapid with the application of load above the upper bound load.

From the free end slip vs number of load cycle curves, for set two, it is found that the rate of increase in free end slip increase in number of cycles is quite rapid upto 0.3 million load cycles and then increases gradaully.

All the beams provided with secondary anchorage failed due to yielding of the strand. There was practically no change in the ultimate capacity of the beams due to pulsating loads.

In pulsating tests, cumulative control deflection depends on the extension of the unbonded portion, cumulative free end slip, straightening and adjustment of the strand. In case of beams without secondary anchorage, cumulative deflection increases at a faster rate in the beginning and then has a gradual increase. Similar is the behaviour of cumulative free end slip with respect to number of load cycles.

For beams with secondary anchorage, cumulative deflection increases in the beginning, which is because of the adjustment of secondary anchorage, straightening and adjustment of

the strand. After about 0.40 mm load cycles the central deflection increases very gradually and tends to become constant.

TABLE 4.1: BOND STRENGTH DETAILS UNDER PULL-OUT TEST

| S.No. | Bonded length (Dia.) | Average ultimate bond strength (MPa) | Average bond stress in initial slip (MPa) | Ratio of (c) to (d) | Ratio of (d) to (c) |
|---|---|---|---|---|---|
| a | b | c | d | e | f |
| 1 | 95 | 2.592 | 2.216 | 1.17 | 0.85 |
| 2 | 118 | 2.202 | 1.471 | 1.49 | 0.67 |
| 3 | 140 | 1.987 | 1.382 | 1.44 | 0.69 |

TABLE 4.2: BOND STRENGTH DETAILS UNDER STATIC BEAM TEST

| S.No. | Beam No. | Bonded length (Dia.) | Stress in the strand at failure (kN) | Ultimate bond strength (MPa) | Stress in the strand at initial slip (kN) | Bond stress at initial slip (MPa) | Ratio of (e) to (g) | Ratio of (g) to (e) |
|---|---|---|---|---|---|---|---|---|
| a | b | c | d | e | f | g | h | i |
| 1 | B-1 | 150 | 1746 | 2.13 | 872 | 1.13 | 1.885 | 0.531 |
| 2 | B-3 | 150 | 1691 | 2.05 | 892 | 1.07 | 1.916 | 0.522 |
| 3 | B-4 | 175 | 1809 | 1.89 | 1008 | 1.05 | 1.800 | 0.556 |
| 4 | B-7 | 140+ Mech. Anch. | 1805 | - | - | - | - | - |

TABLE 4.3: BOND STRENGTH DETAILS UNDER PULSATING LOAD TESTS

| Set No. | Bonded length (Dia) | Type of Test | Beam No. | Upper load in terms of | | Lower load in terms of | | Number of load cycles x10$^6$ | Mode of failure | Ultimate stress in terms of | | Stress in the strand under Pulsating Load | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Jack capacity percent | Bond stress MPa | Jack capacity percent | Bond stress MPa | | | Stress in the strand kN | Bond stress MPa | Upper Load kN | Lower Load kN |
| | – | Static | B-1 | – | – | – | – | – | Bond | 1745 | 2.13 | – | – |
| I | 150 | – | B-3 | – | – | – | – | – | Bond | 1680 | 2.05 | – | – |
| | | Pulsating | B-2 | 16 | 1.15 | 12 | 0.86 | 0.025 | Bond | 1398 | 1.83 | 939 | 706 |
| | | Static | B-4 | – | – | – | – | – | Bond | 1808 | 1.89 | – | – |
| II | 176 | Pulsating | B-5 | 16 | 1.1 | 12 | 0.76 | 1.020 | Bond | 1524 | 1.59 | 960 | 728 |
| | | -do- | B-6 | 16 | 1.1 | 12 | 0.76 | 1.058 | Bond | 1563 | 1.64 | 960 | 728 |
| | | Static | B-7 | – | – | – | – | – | Tensile | 1805 | – | – | – |
| III | 140 + Mech. Anch. | Pulsating | B-8 | 20 | – | 15 | – | 1.008 | Tensile | 1839 | – | 1163 | 888 |
| | | -do- | B-9 | 20 | – | 15 | – | 1.029 | Tensile | 1834 | – | 1163 | 888 |

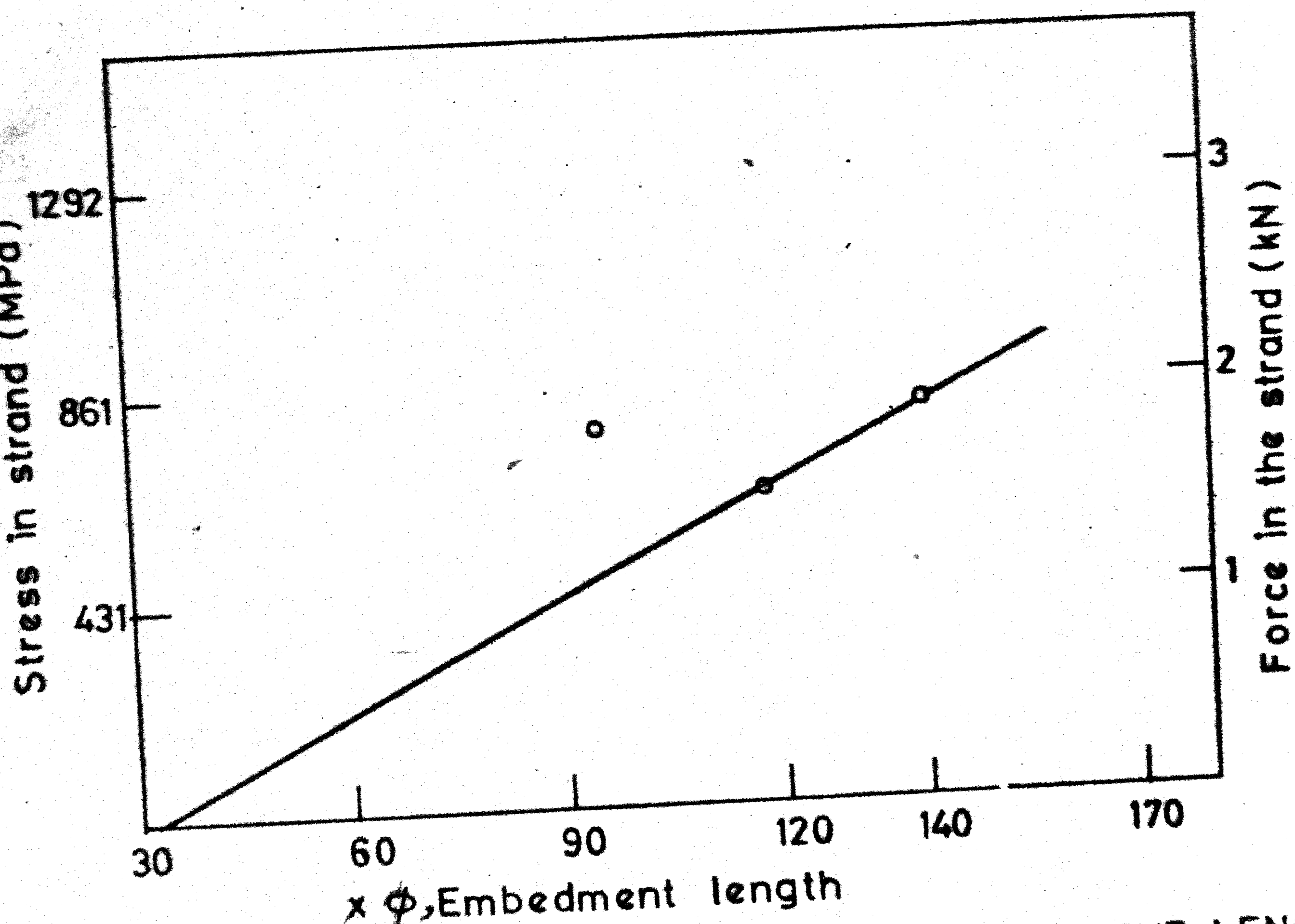



FIG. 4.1 STRESS IN STRAND VS EMBEDMENT LENGTH

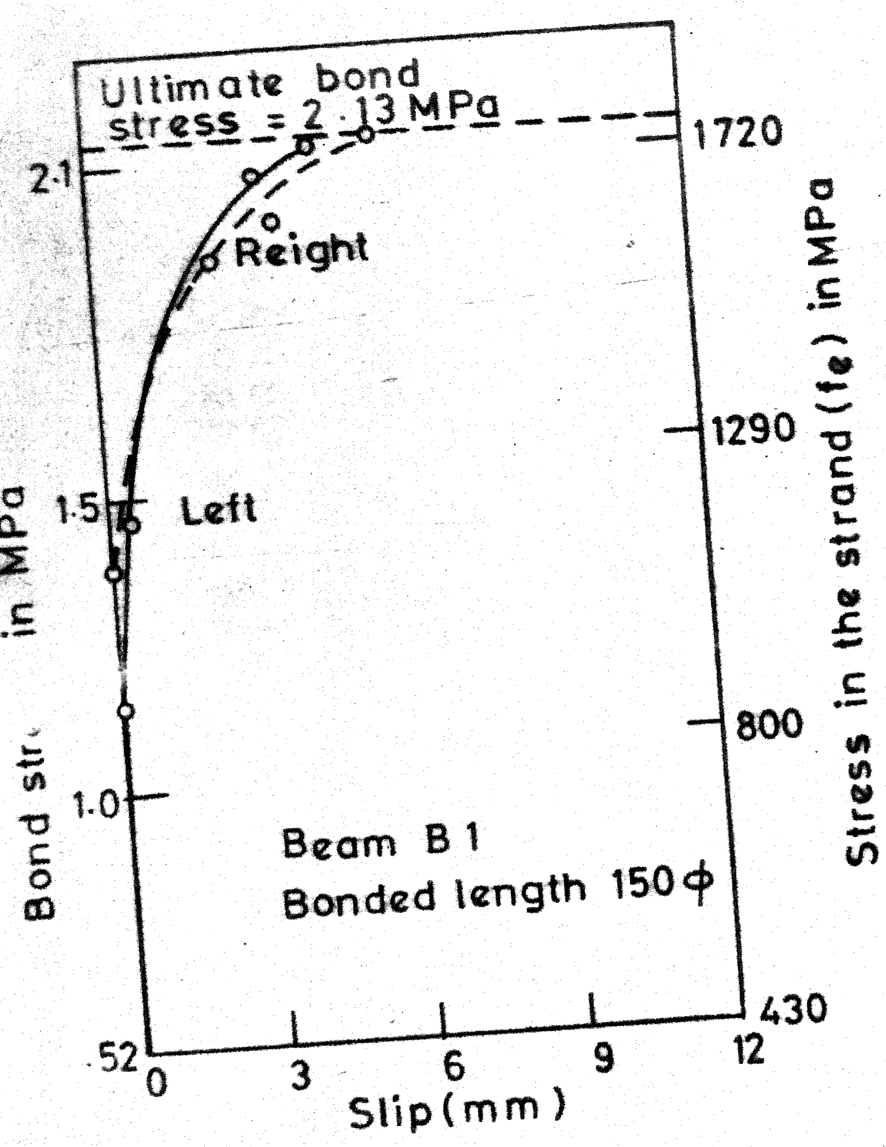



FIG. 4.2 BOND STRESS VS. SLIP UNDER STATIC LOAD

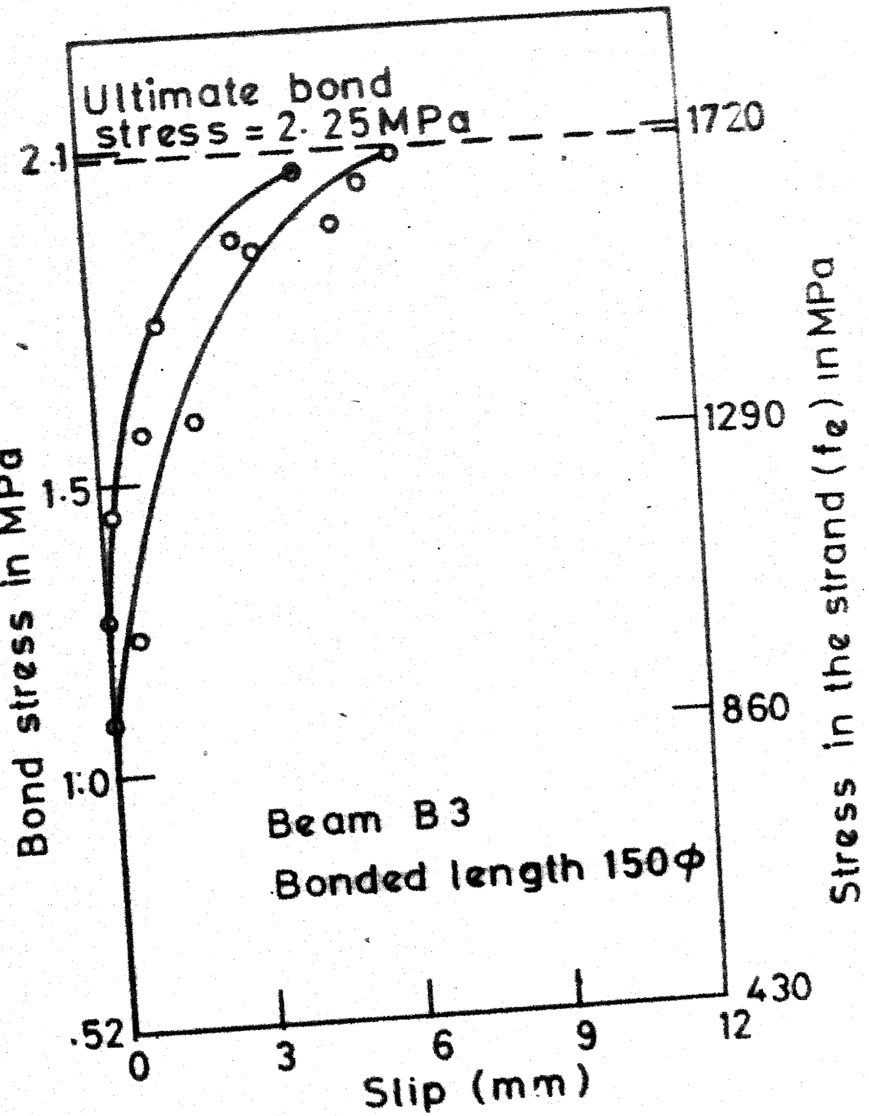



FIG. 4.3 BOND STRESS VS. SLIP UNDER STATIC LOAD

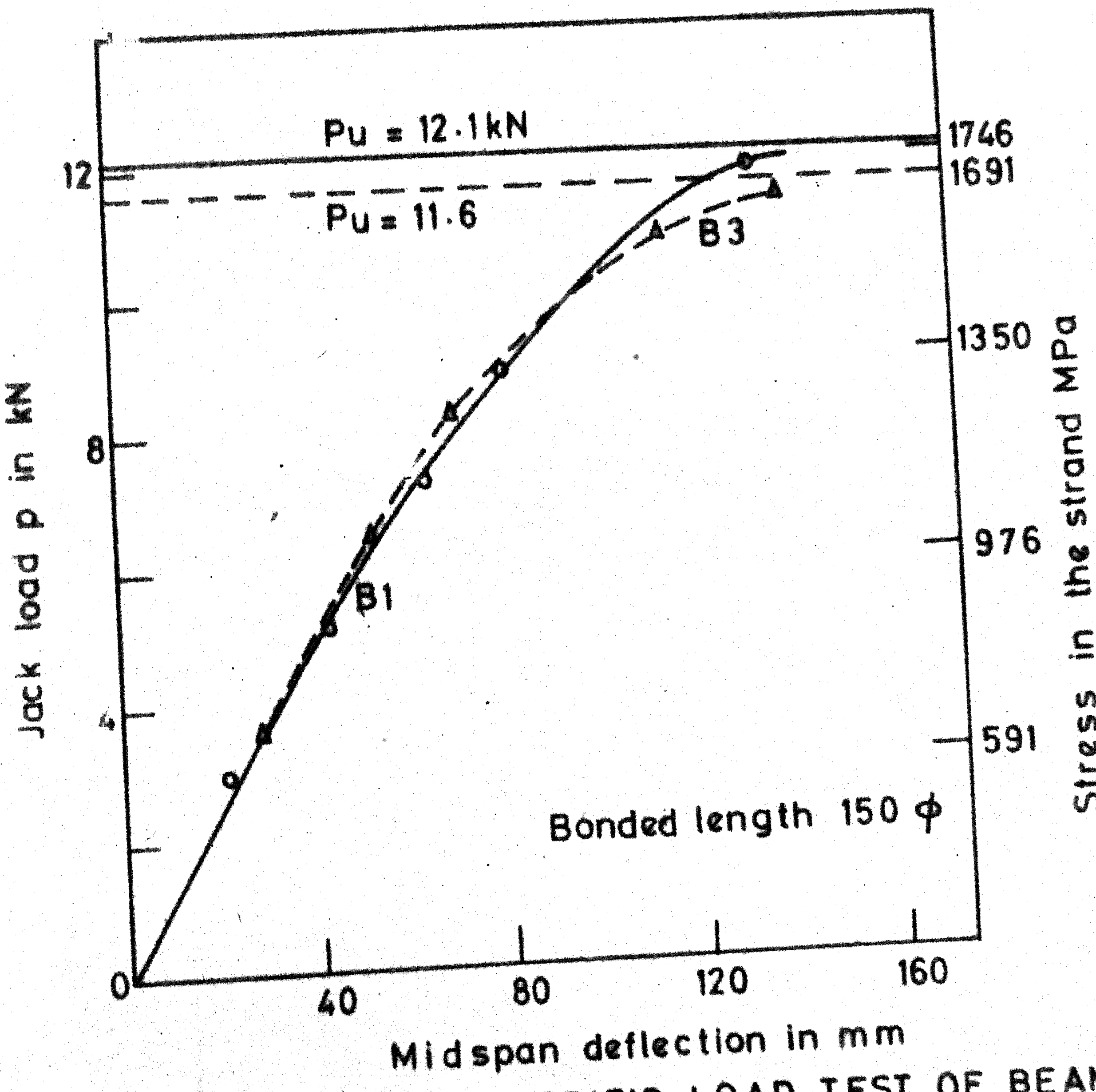



FIG. 4.4 ULTIMATE STATIC LOAD TEST OF BEAM B1 AND B3

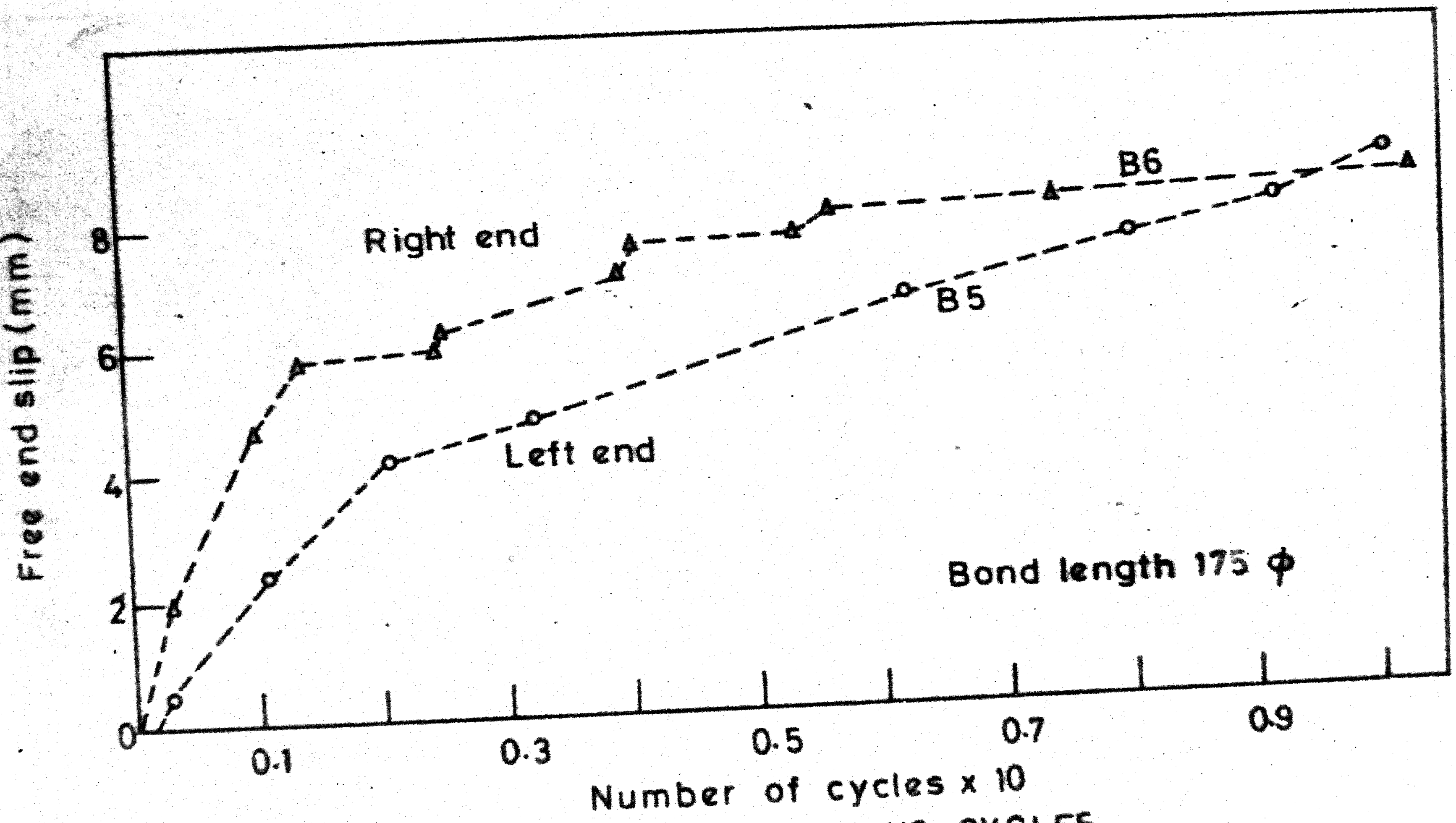



FIG. 4.7 FREE END SLIP VS. CYCLES

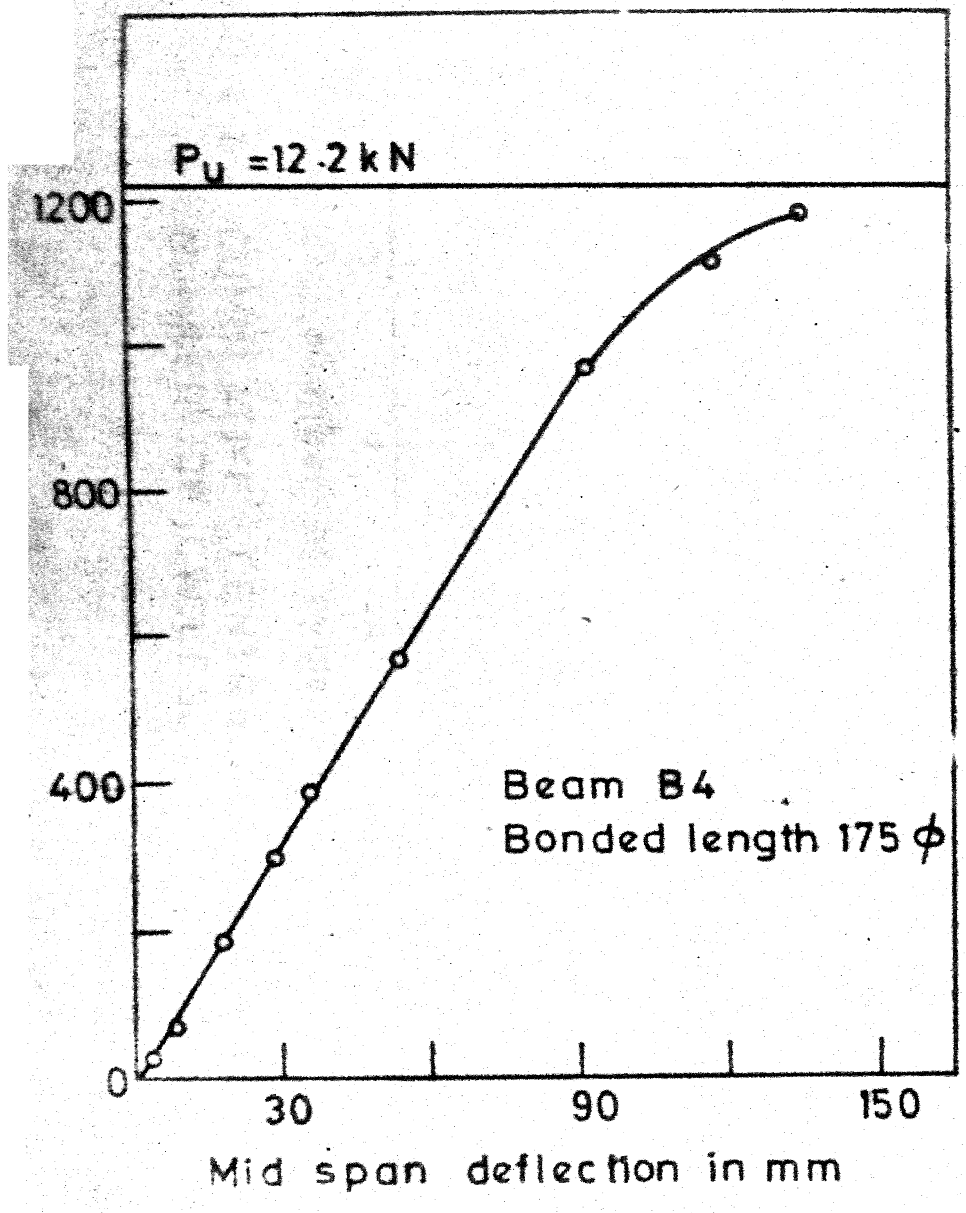



FIG.4.5 LOAD DEFLECTION CURVE FOR BEAM B4

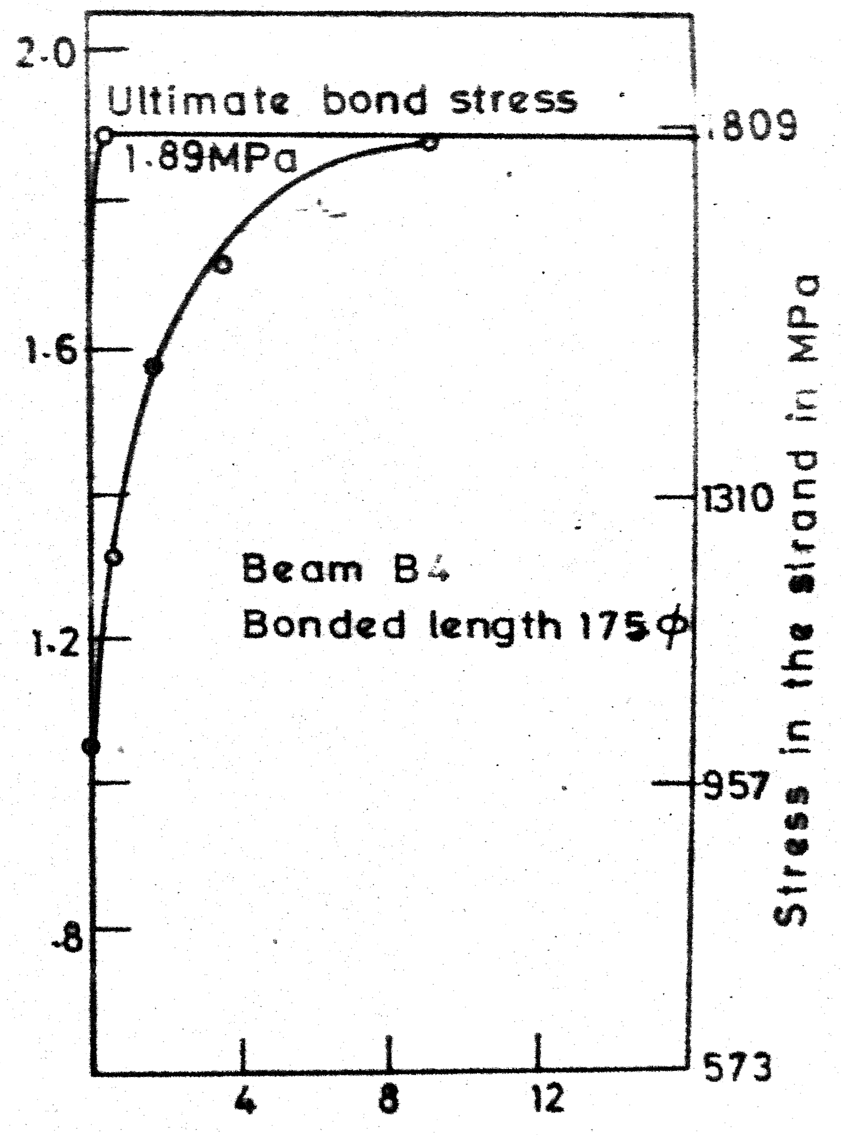



FIG.4.6 BOND STRESS VS. FREE END SLIP

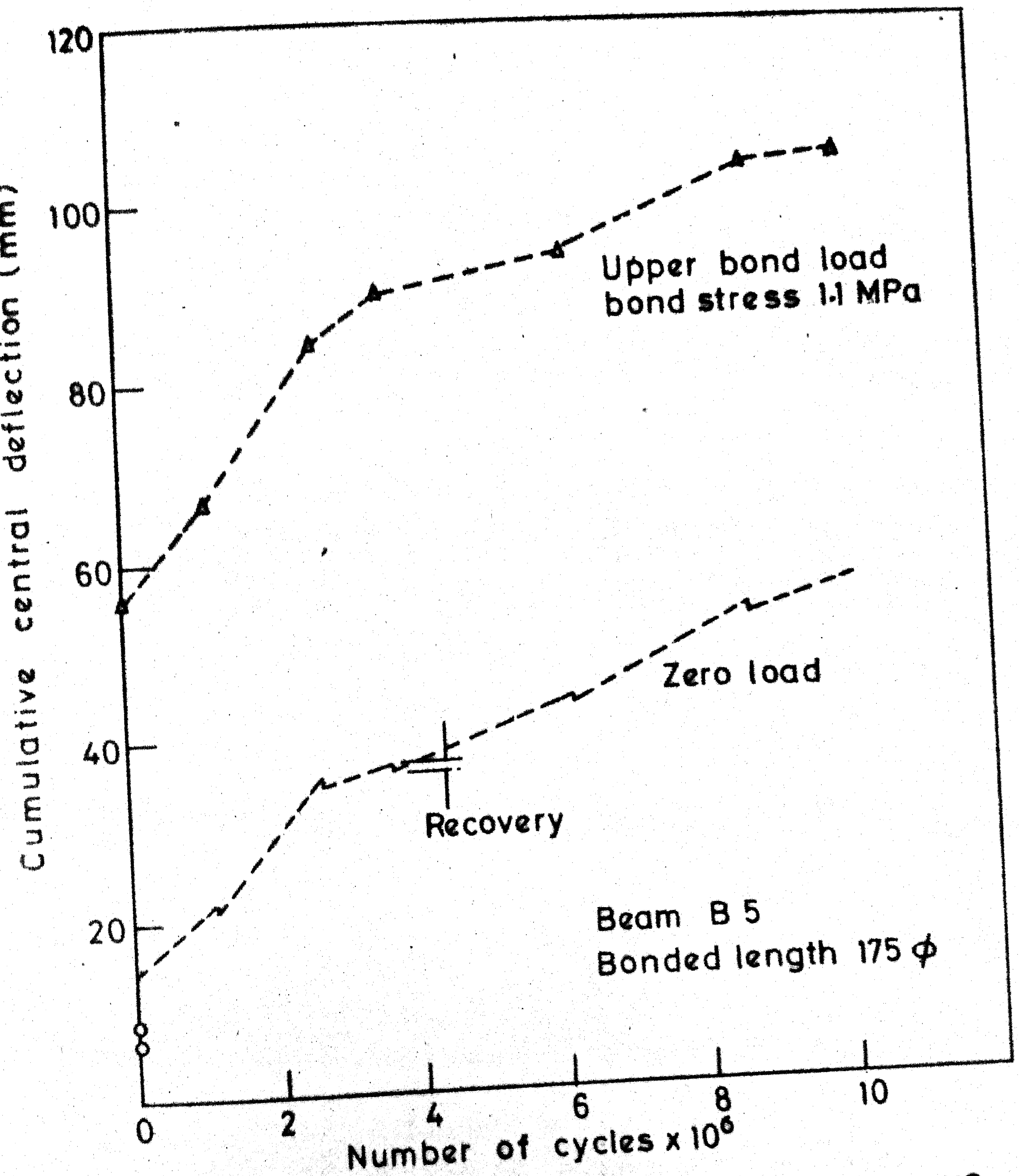



FIG. 4.8 CUMULATIVE CENTRAL DEFLECTION VS. NUMBER OF CYCLES.

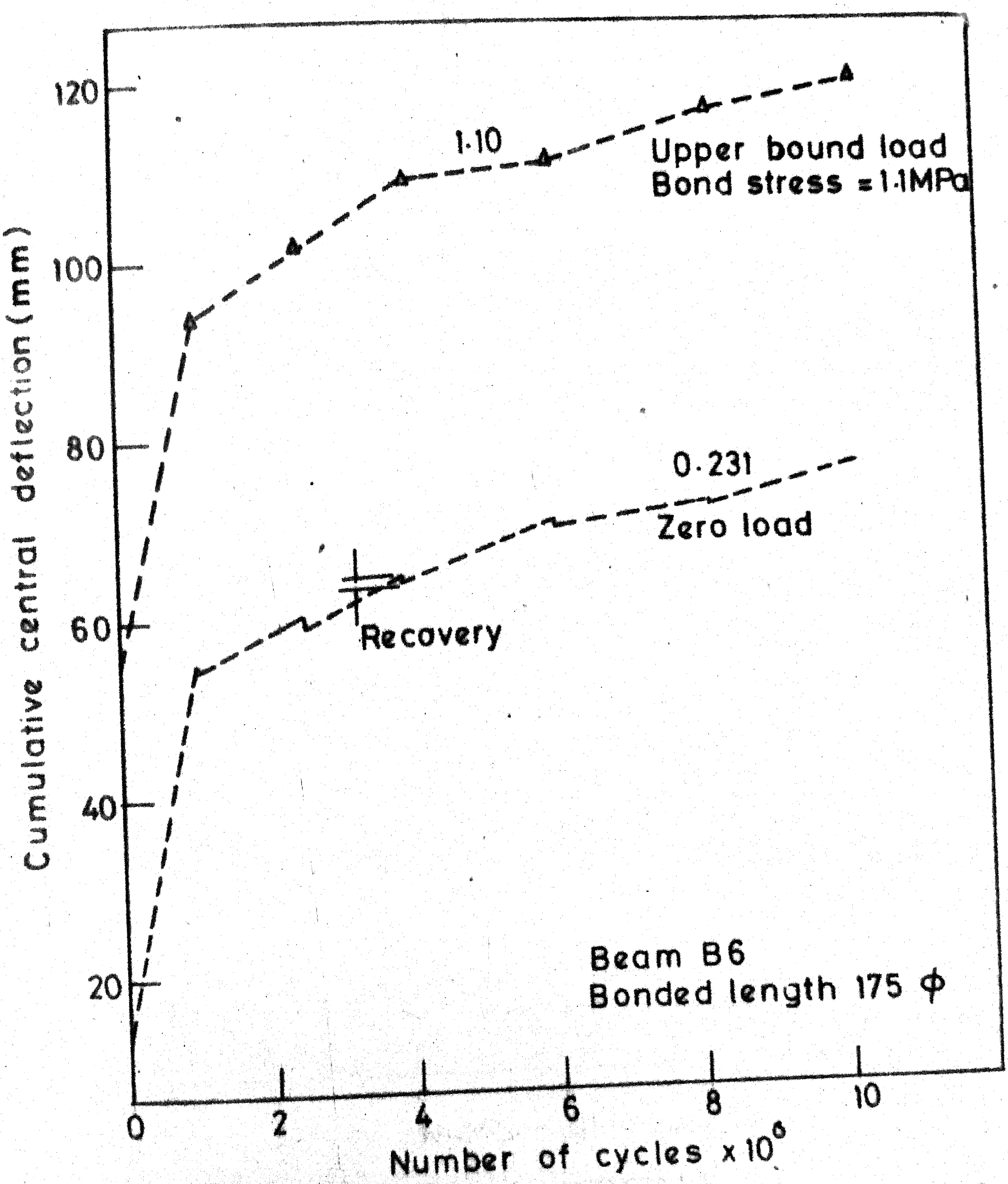



FIG. 4.9 CUMULUTIVE CENTRAL DEFLECTION VS. NUMBER OF CYCLES.

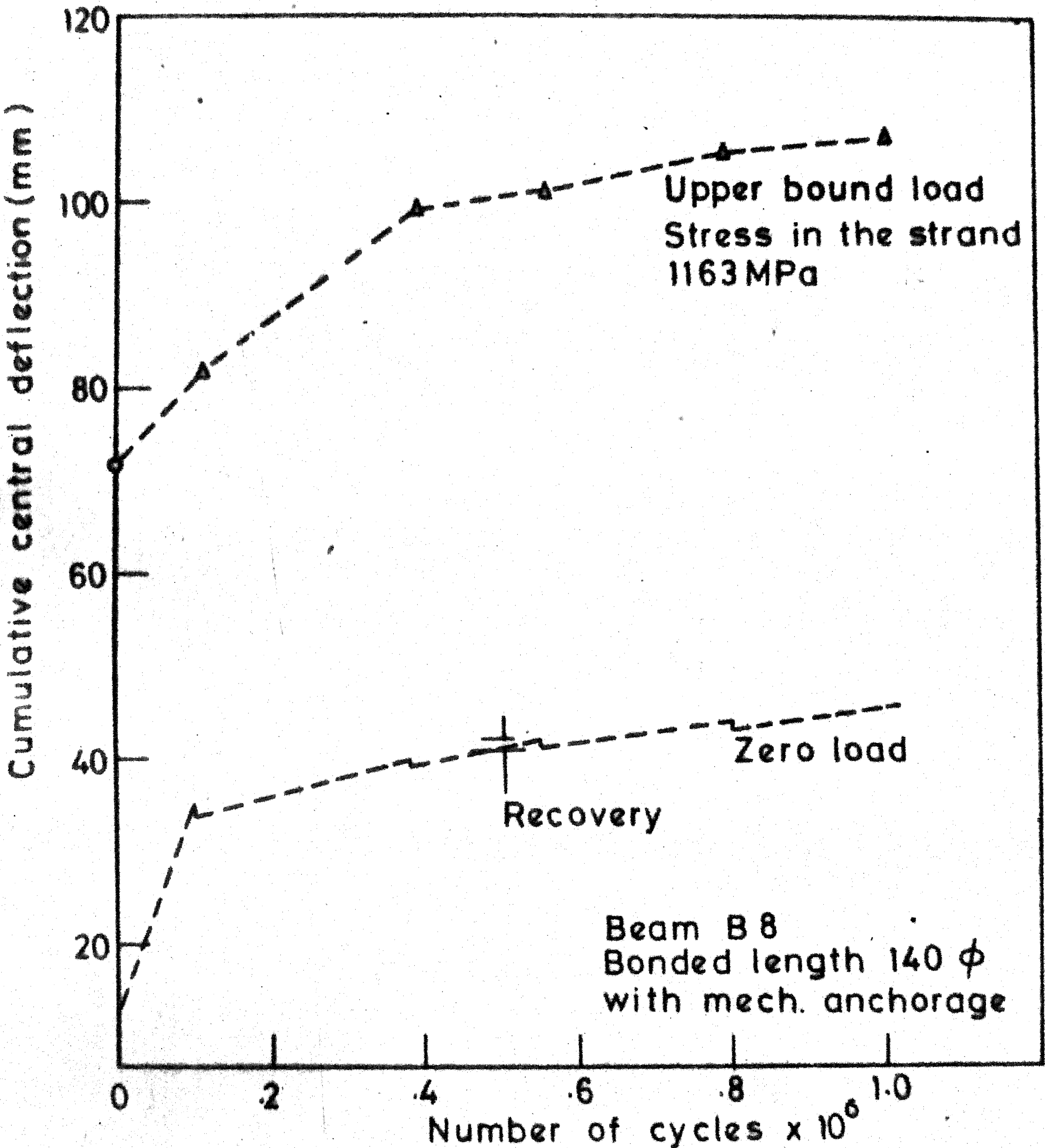



FIG. 4.10 CUMULATIVE CENTRAL DEFLECTION VS. CYCLES

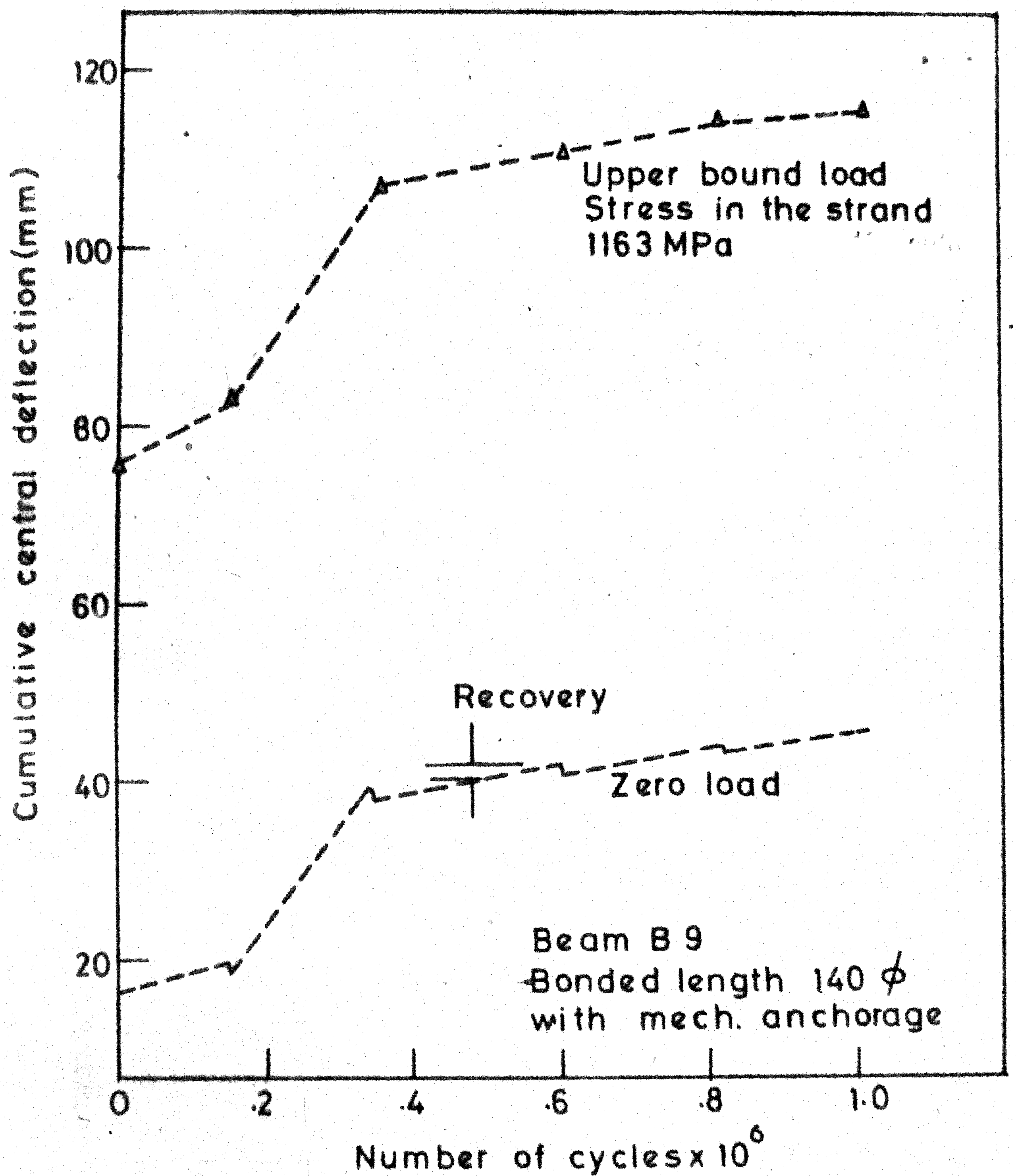



FIG. 4.11 CUMULATIVE CENTRAL DEFLECTION VS. NUMBER OF CYCLES

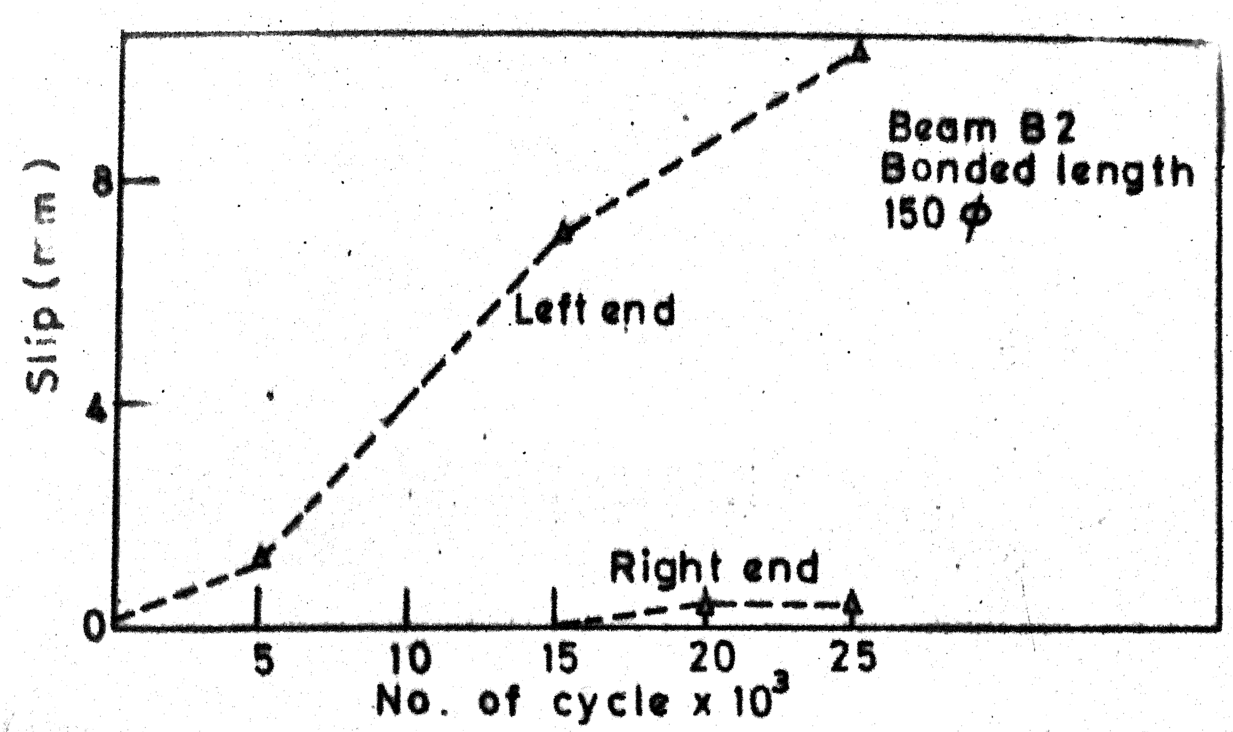



FIG.4.12 SLIP VS CYCLES FOR BEAM B2

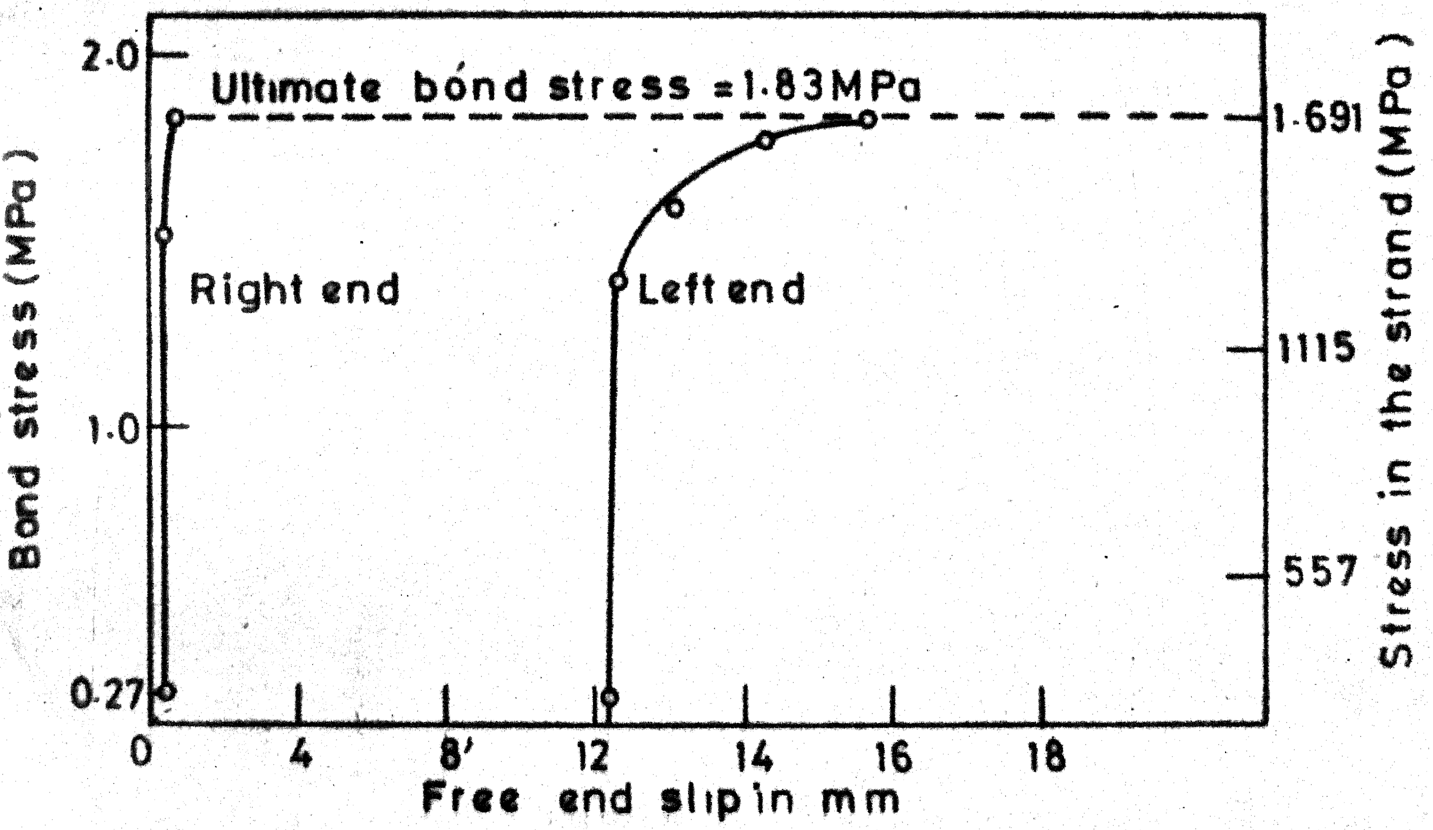



FIG. 4.13 BOND STRESS VS. FREE END SLIP FOR BEAM B2

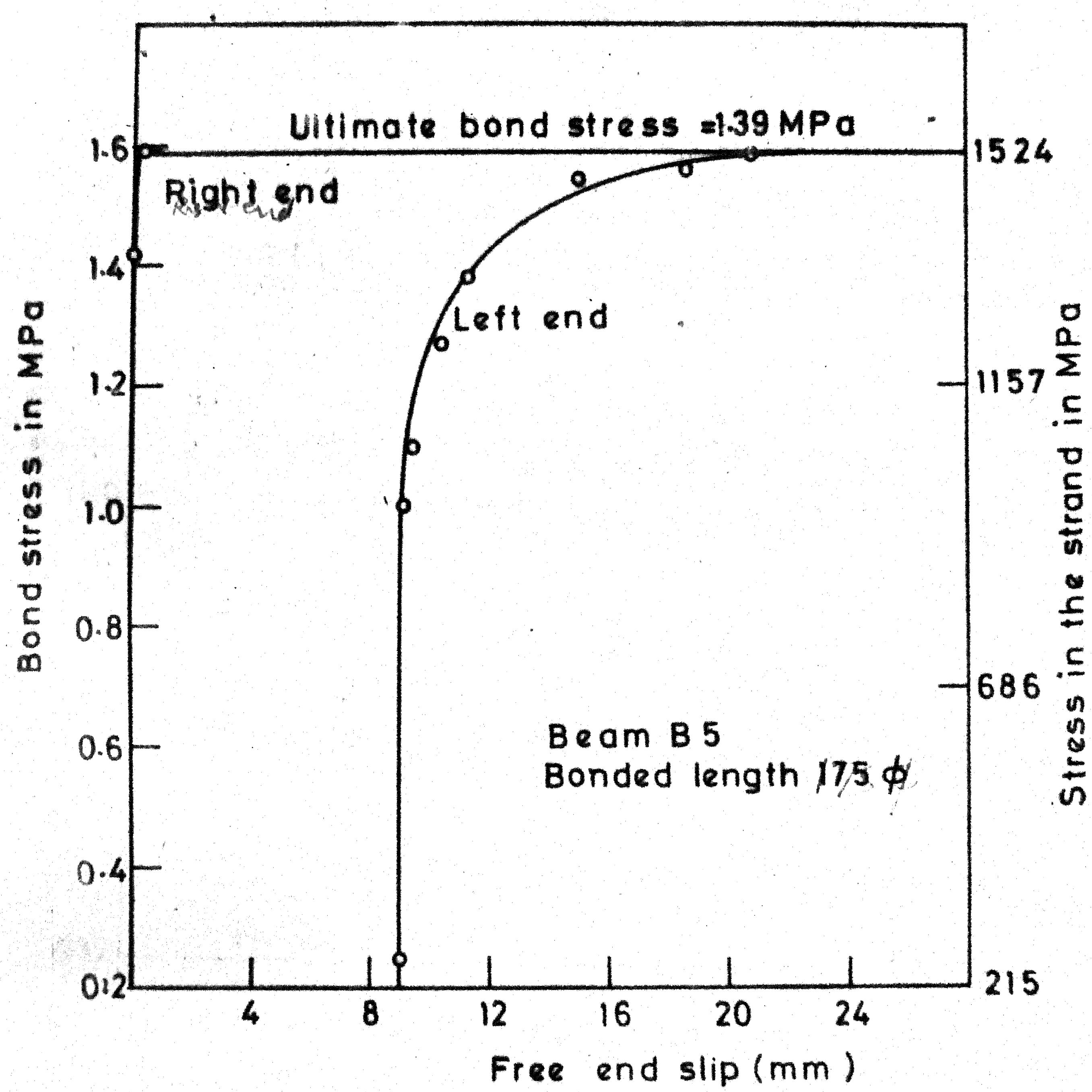



FIG. 4.14 BOND STRESS VS SLIP CURVE UNDER POST PULSATING STATIC LOAD

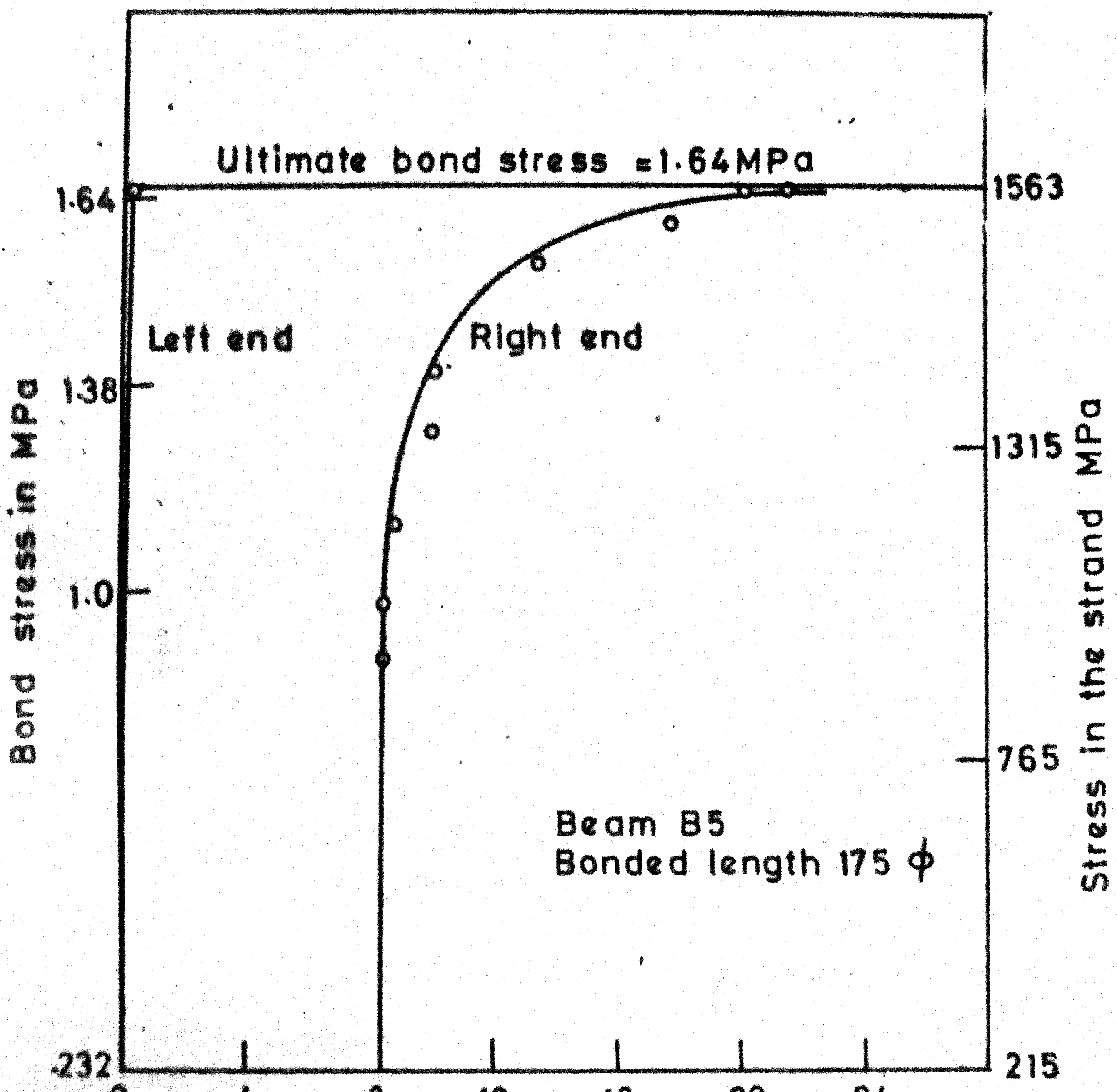



FIG. 4.15 BOND STRESS VS. SLIP CURVE UNDER POST PULSATING STATIC LOAD

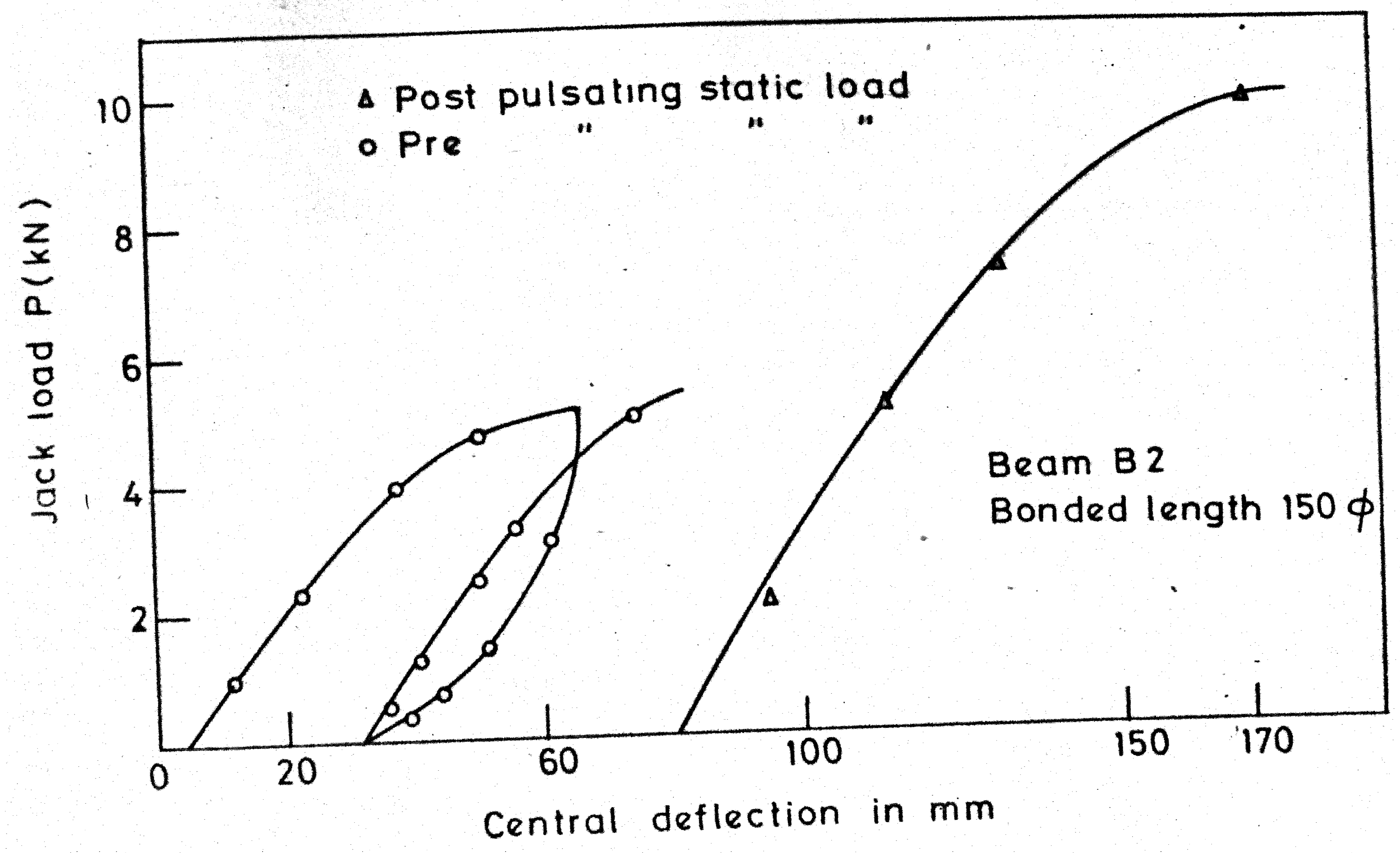



FIG. 4.16 JACK LOAD VS. CENTRAL DEFLECTION.

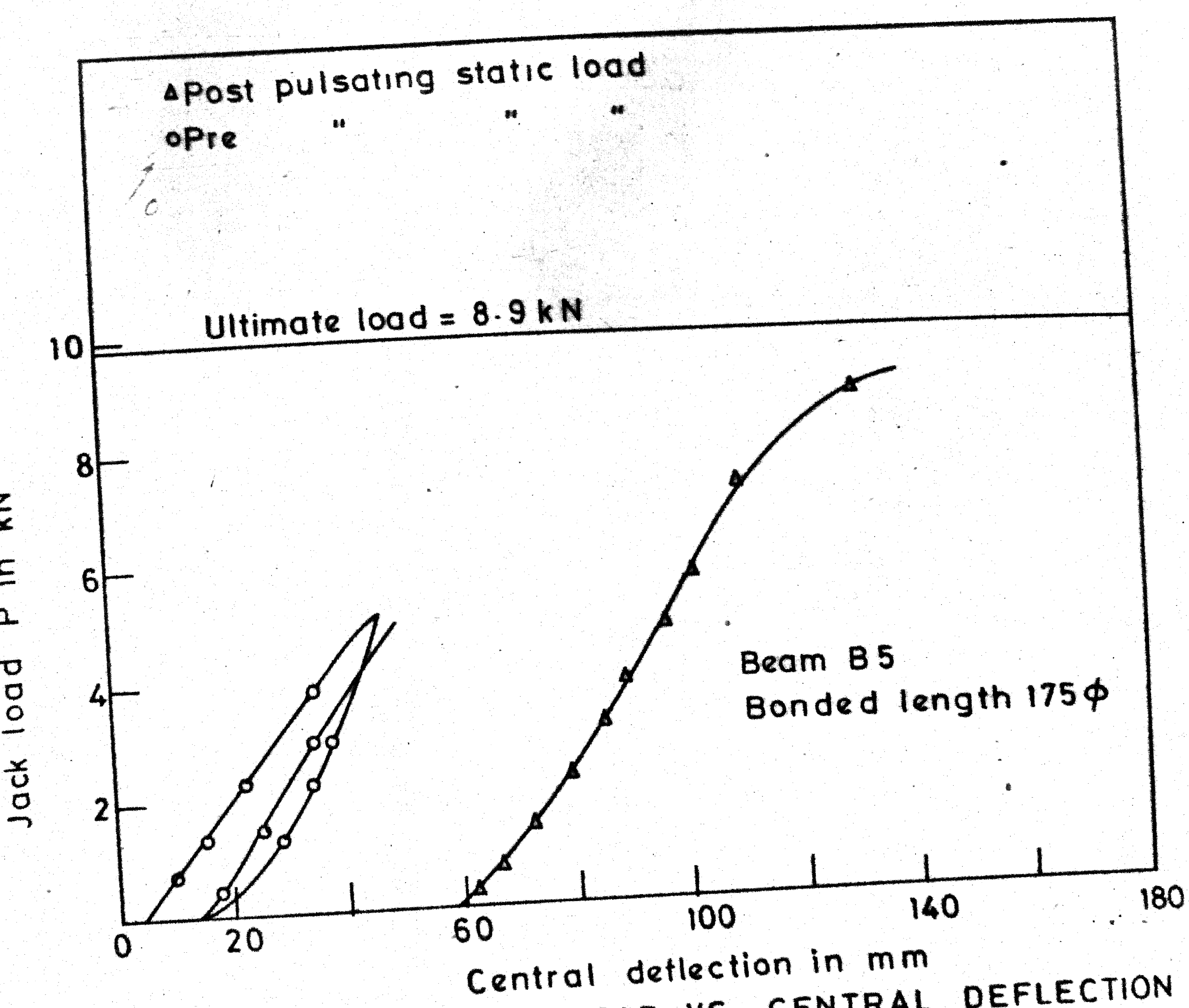



FIG. 4.17 JACK LOAD VS CENTRAL DEFLECTION

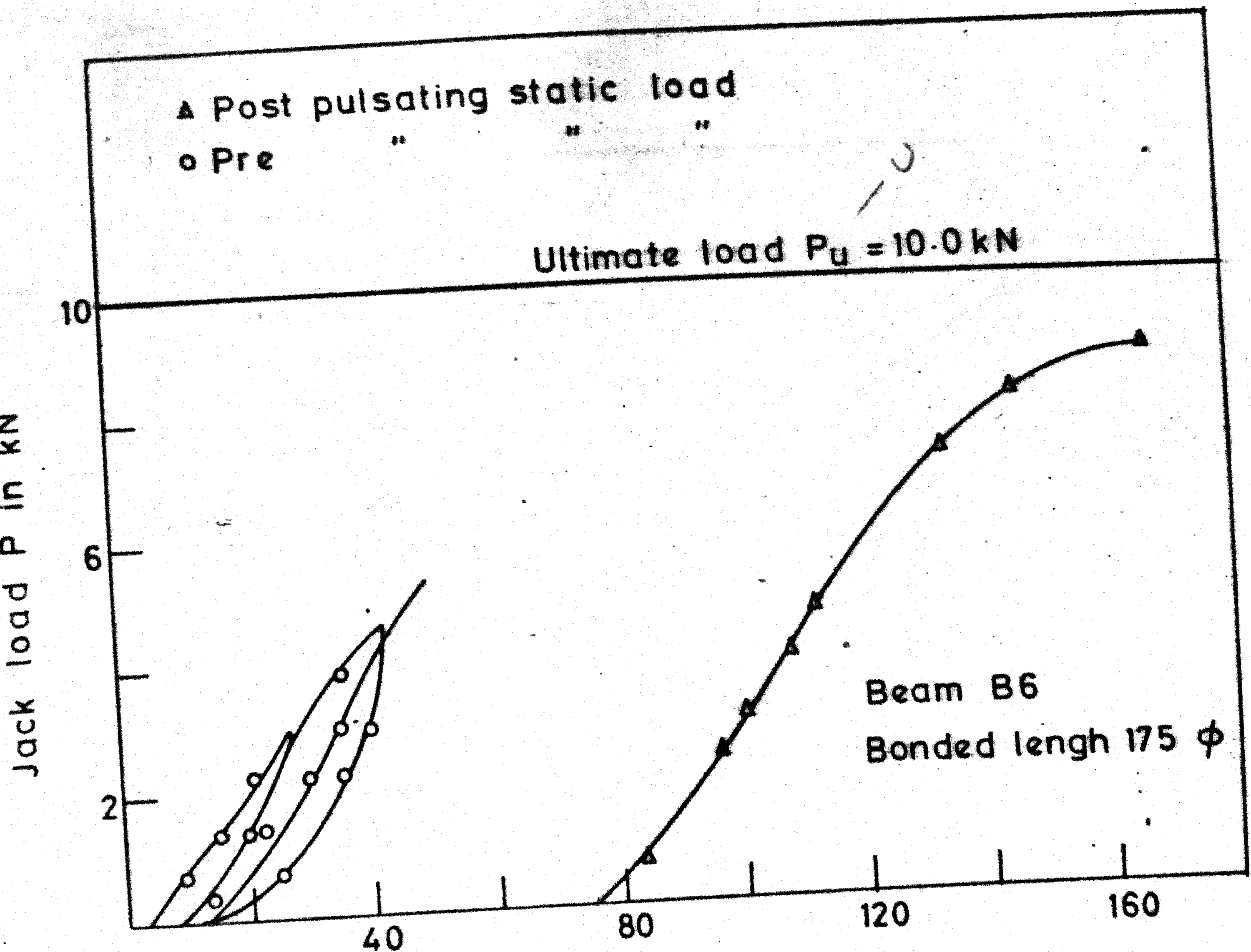



FIG. 4 18 JACK LOAD VS CENTRAL DEFLECTION

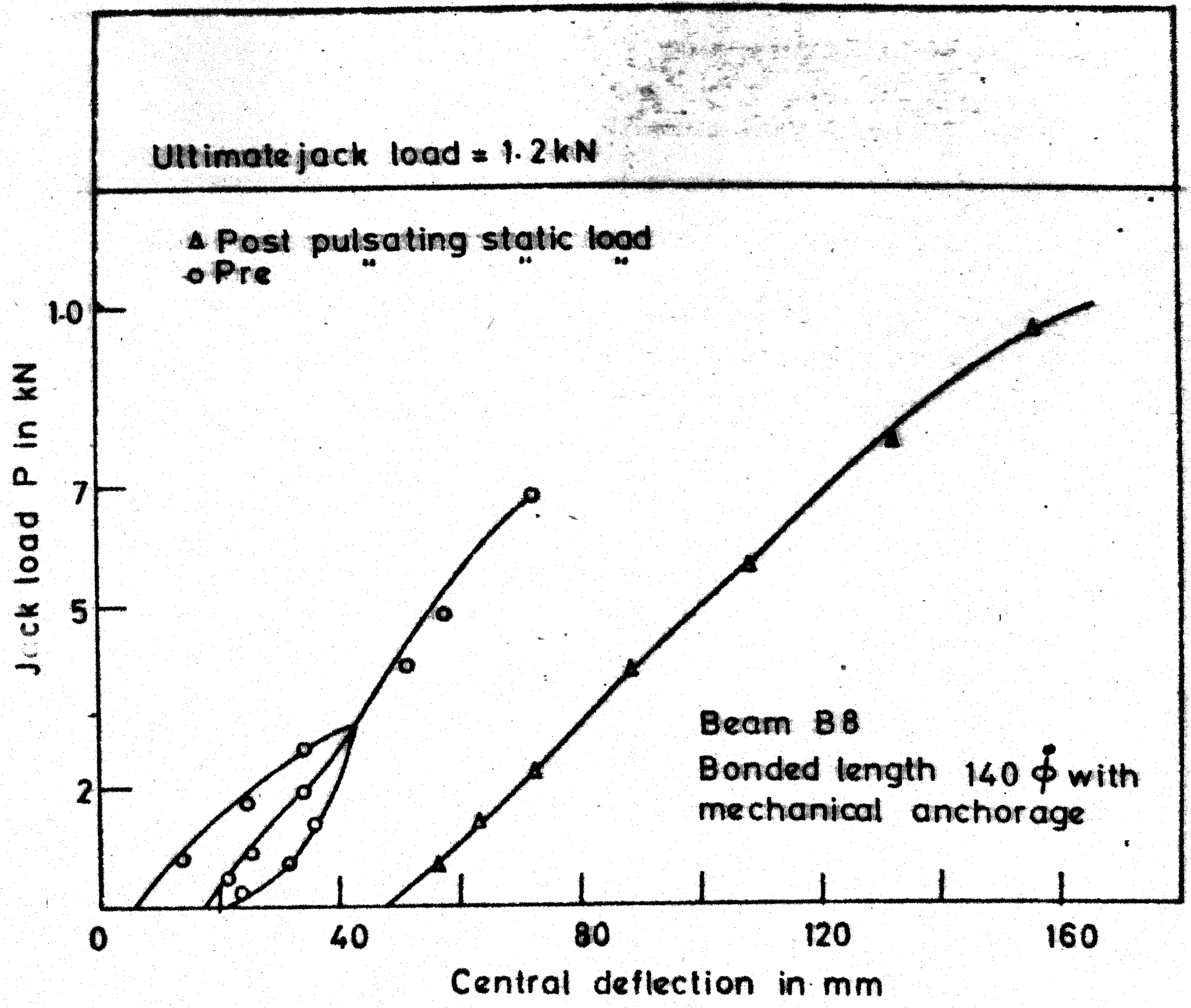



FIG. 4 19 JACK LOAD VS CENTRAL DEFLECTION

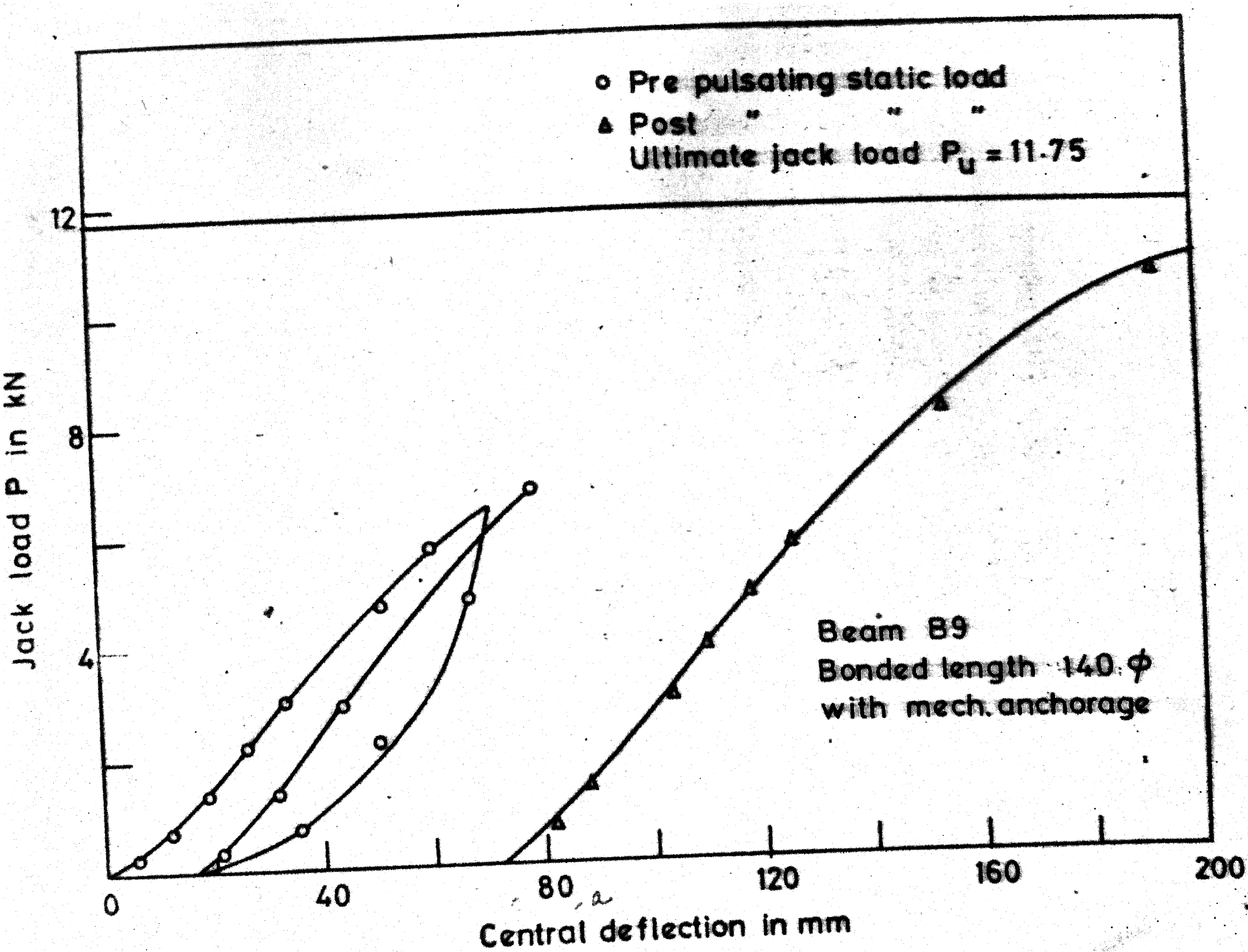



FIG. 4.20 JACK LOAD VS. CENTRAL DEFLECTION

# CHAPTER - V

# CONCLUSIONS

## 5.1 : INTRODUCTION:

Bond behaviour of strands in prestressed concrete members depends on a number of factors in which method of construction plays an important role. Sometimes, due to defective construction or practical constraints, the strands may develop only partial bond due to which it may fail prematurely under pulsating loads. An attempt to study the behaviour of partially bonded strands under pulsating loads is made.

The following conclusions can be drawn from the experimental investigation.

## 5.2 : PULL -OUT TEST:

(i) Bond strength decreases with increase in the embedment length. This is due to the fact that in pull-out test with longer embedment lengths, the high bond stress developed at the pulling end decreases gradually and tends to zero at the free end. But for specimens with shorter embedment lengths the decrease in bond stress is not that gradual, thus shorter embedment lengths give higher average bond strength.

(ii) Even after initial slip, the bonded strand has some more capacity to transfer the force. The ratio of average bond strength to the average bond stress at

initial slip for specimens with embedment length as 95 Ø, 118 Ø and 140 Ø came out as 1.17, 1.49 and 1.44 respectively. When the failure is considered by total slip of the strand, the reserve bond strength of strands increases with increase in the embedment lengths.

(iii) An equation, for a strand of 6.35 mm dia (1/4 inch), embedded straight, was derived to evaluate the stress in the strand for a given embedment length and it is:

$$\sigma_s = 1.2\ L_e - 240 \qquad (5.1)$$

The above equation gives slightly lower values as compared with those given by Salmons (10).

## 5.3 : BEAM TESTS:

### 5.3.1 : STATIC LOAD TEST:

(i) For beams with bonded length of 150 Ø and 175 Ø, the initial free end slip occured at a stress of 52% and 59% of proof stress, respectively.

(ii) The average bond stress at initial free end slip for bonded length of 150 Ø was 1.10 MPa while for bonded length of 175 Ø it was 1.07 MPa.

(iii) The stress in the strand at the time of ultimate slip failure was about the same as proof stress for beams with bonded lengths as 150 Ø and 175 Ø.

(iv) Even though the strand with embedment length of 150 Ø may have an initial slip, it can withstand a stress close to the proof stress before total slip.

Slip, in general, affects the serviceability of the structure. Therefore embedment lengths in the range of 150 ∅ are not safe. In case of pretensioned prestressed concrete beams, Hoyer effect is likely to have additional benefit when compared with the untensioned ones.

(v) Specimen with bonded length of 140 ∅ and provided with secondary anchorage failed due to yielding of the strand.

5.3.2 : PULSATING TESTS ON BEAMS:

(i) Free End Slip:

(a) For beams with embedment length of 150 ∅, the free end slip increases with increase in number of load cycles. The cumulative slip was 10.4 mm. in about 25000 load cycles.

(b) For beams with embedment length of 175 ∅, the free end slip increases with increase in the number of load cycles. However, the rate of increase of slip in the first 0.3 million load cycles is higher than that after 0.3 million load cycles.

(c) The strands acquired permanent free end slips under pulsating loads and there was no recovery of the slip at the release of loads. The free end

slip under pulsating loads is discontinuous and occurs in jerks after an arbitrary number of cycles.

(ii) Cumulative Deflections:

(a) Beams with embedment length of 175 ∅ –

The cumulative deflection for 0.4 million load cycles at a strand stress of 960 MPa was about 1.8 times the initial static deflection while for one million load cycles it was 2.02.

(b) Beams with secondary anchorage and embedment lengths of 140 ∅ :–

The cumulative deflection for 0.4 million load cycles at a strand stress of 1163 MPa was about 1.44 times the initial static deflection while after one million load cycles it was 1.53.

(iii) Residual Deflection:

(a) All beams gave a residual deflection when subjected to two cycles of static load upto upper load limit.

(b) Under pulsating loads, the residual deflections increased at a higher rate for first 0.4 million load cycles, for beams with bonded length of 175 ∅ and beams with secondary anchorage. The residual deflection gets stabilized after 0.4 million cycles in case of beams with secondary anchorage.

(c) For beams with bonded length 175 ∅, the relative residual deflection with respect to the initial deflection at the upper load was 0.22 and for beams with secondary anchorage it was 0.24.

(d) There was negligible recovery in the residual deflection after the release of loads.

(iv) For beams with bonded length of 150 ∅ and 175 ∅, the bond capacity of the beams tends to deteriorate due to the pulsating loads and the reduction in capacity was in the range of 10 to 15%.

(v) A number of tendons are usually provided to impart a desired prestressing force in a prestressed concrete beam. A tendon which has developed only a partial bond will slip-in cumulatively under pulsating loads. Hence there will be a decrease in the total prestressing force thus reducing the load carrying capacity of the beam. This capacity goes on decreasing as the number of cycles increases. A provision of secondary anchorage to a partially slipped strand eliminates bond failure of the strand. Thus the load carrying capacity is about the same as that of a well bonded system. However, the deflection in such a beam will be more than that of a fully bonded beam and can be called as a mixed pre-

tensioned and post-tensioned unbonded type of beam.

## 5.3 : Post-Pulsating Static load tests:

After application of pulsating load cycles, the specimen acquires a permanent free end slip from zero to upper load level. However, the strand exhibits some stress transfer capacity during post-pulsating static load tests, although the rate of increase in free end slip is quite rapid with the increase in the load beyond upper load level. The strength of the beams with secondary anchorages was unaffected with a million cycles of load.

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# APPENDIX - A

Hinged beam were chosen so as to develop direct tension on the strand. Since in the present study bond was the main paramter, a hinged beam, which would be safe in all other respect, viz. crushing and shear was selected. Such a beam when subjected to two point loading as shown in Fig. A.1, the moment developed will produce compression on the hinge and tension in the strand. Moment at the centre due to weight of beam and girder $M_1 = \frac{W_b L}{8} + \frac{W_g}{2} a$

Moment due to applied Jack load

$$M_2 = \frac{P}{2} a$$

Total moment at the centre

$$M_T = \frac{W_b L}{8} + \frac{W_g a}{2} + \frac{P}{2} a$$

For equlibrium, $M_T = Fj$

$$\text{Therefore, } F = \frac{1}{j} \left( \frac{W_b L}{8} + \frac{W_g a}{2} \right) + \frac{P}{2} a \; ) \qquad - \text{A.1}$$

Before starting the tests on a particular beam the values of L, a, $W_b$ and $W_g$ were noted. The value of 'g' depends on the load, P, applied through the jack. From EQ. A.1, tension in the strand can be calculated.

The dimensions of all the beams were taken as D = 200 mm, B = 80mm. The beam was checked for crushing at the hing and shear at the supports. One legged 6mm dia stirrups at 150 mm c/c were welded to two 10mm bars so as to provide extra precaution against shear. The length of the beam was taken so as to give a maximum of 220 Ø embedment length. The different parameters in EQ. A.1. are

F = Tension in the strand.

C = Compression at the hinge.

a = Shear Span.

L = Effective Span of hinged beam.

g = Distance between centre of hinge to centre of strand.

$W_b$ = Weight of beam.

$W_g$ = weight of girder.

P = Load applied through the Jack.

Ø = diameter of strand.

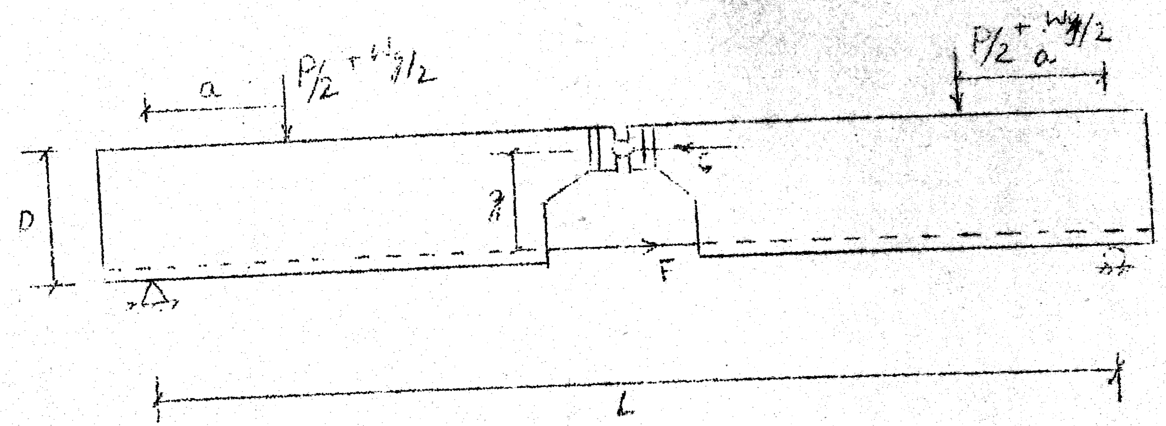


FIG. A.1 HINGED BEAM AND LOAD POINTS

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